Muon Campus

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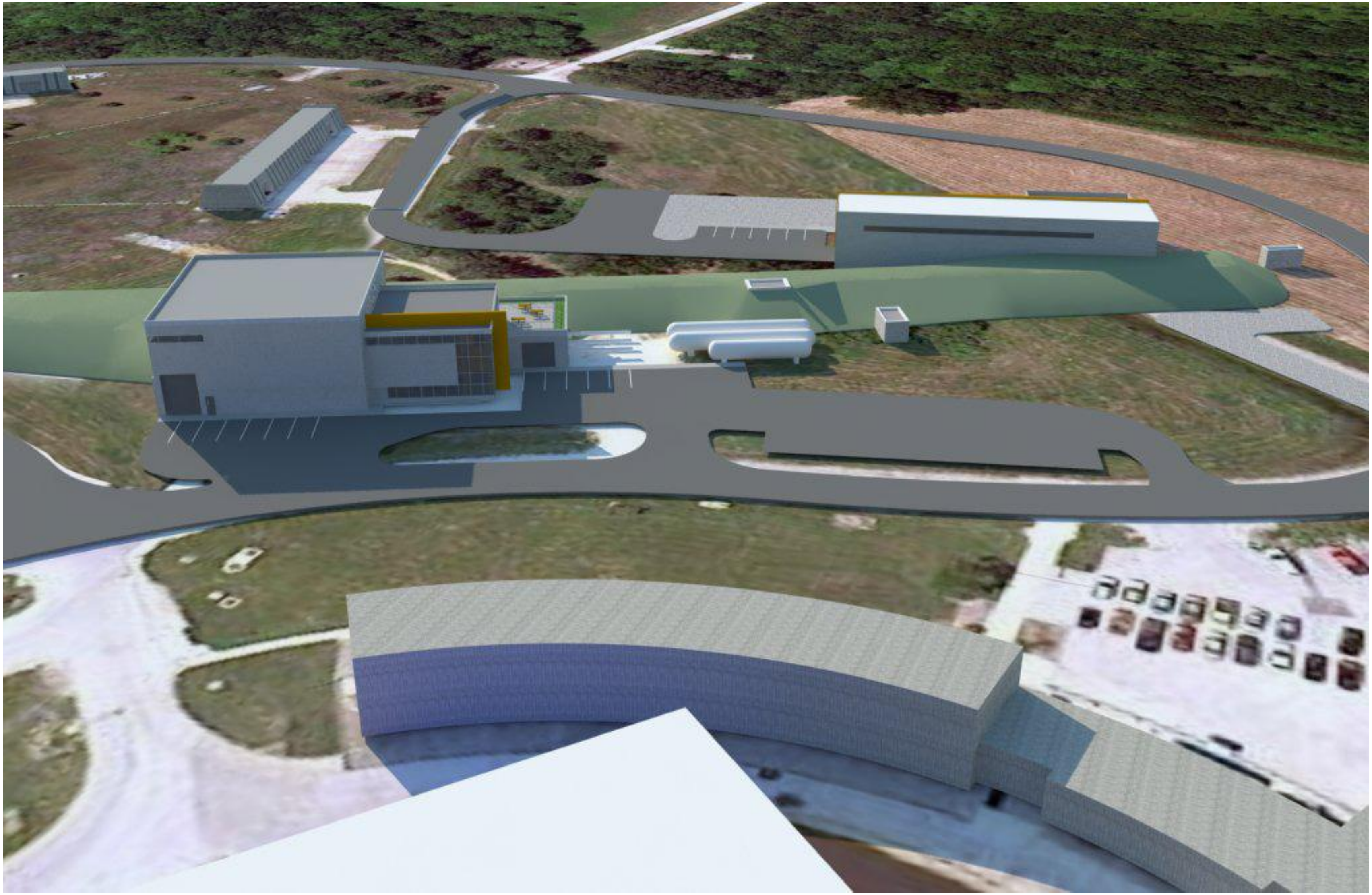
Fermilab Undergraduate Lecture Series

17 June 2014

Muon Campus layout

Looking toward the Muon Rings

View from Wilson Hall

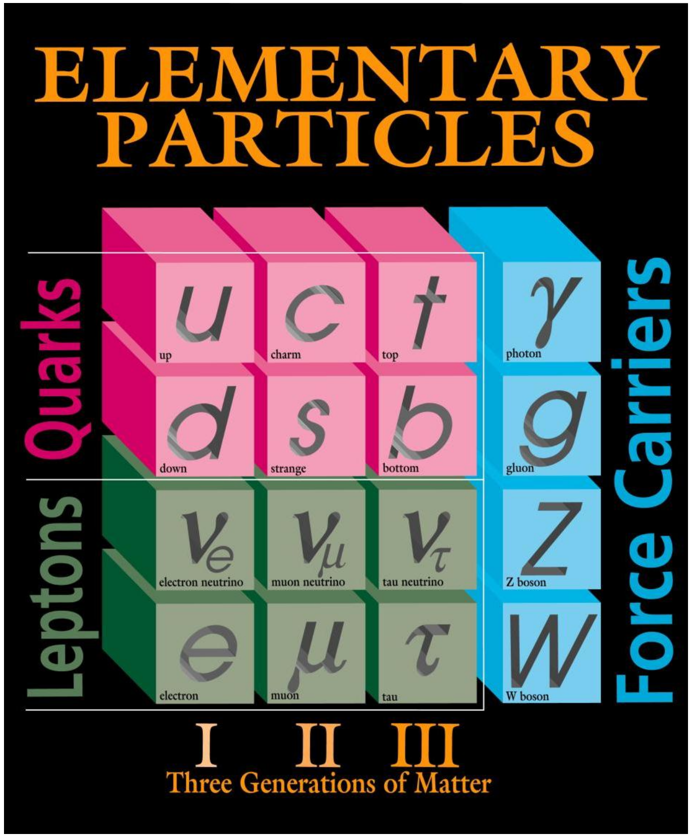


Muon Campus construction in progress

MC-1 building
- g-2 and future experiments
- cryo refrigerator system for g-2 and Mu2e
- power supplies for some beamline components
- 80’ x 80’ high-bay with 30 T crane, internal loading dock
- Floor stable, load-bearing to 700 T, excellent temperature control

Muons

- Heavier cousin of the electron (105.7 MeV)
- Decays to electron and neutrinos with average lifetime 2.2μs in rest frame



Muon Campus experiments

- Two new experiments
- g-2
  - Measure the muon anomolouos magnetic moment to high precision
  - Much of same collaboration from g-2 experiment at Brookhaven National Lab
  - Expected to start taking data in 2017
- Mu2e
  - Search for muon to electron conversion
  - Expected to start taking data in 2019????

Anomalous magnetic dipole moment

From Wikipedia, the free encyclopedia

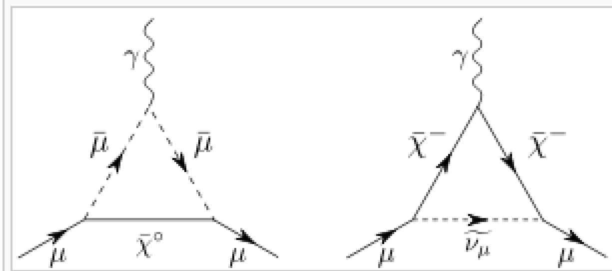
In quantum electrodynamics, the **anomalous magnetic moment** of a particle is a contribution of effects of quantum mechanics, expressed by Feynman diagrams with loops, to the magnetic moment of that particle. (The *magnetic moment*, also called *magnetic dipole moment*, is a measure of the strength of a magnetic source.)

The "Dirac" magnetic moment, corresponding to tree-level Feynman diagrams (which can be thought of as the classical result), can be calculated from the Dirac equation. It is usually expressed in terms of the g-factor; the Dirac equation predicts $g = 2$. For particles such as the electron, this classical result differs from the observed value by a small fraction of a percent. The difference is the anomalous magnetic moment, denoted a and defined as

$$a = \frac{g-2}{2}$$

Anomalous magnetic moment of the muon [edit]

The anomalous magnetic moment of the muon is calculated in a similar way; its measurement provides a precision test of the Standard Model. The prediction for the value of the muon anomalous magnetic moment includes three parts: $\alpha_\mu^{SM} = \alpha_\mu^{QED} + \alpha_\mu^{EW} + \alpha_\mu^{had}$. The first two components represent the photon and lepton loops, and the W boson and Z boson loops, respectively, and can be calculated precisely from first principles. The third term represents hadron loops, and cannot be calculated accurately from theory alone. It is estimated from experimental measurements of the ratio of hadronic to muonic cross sections (R) in e^+e^- collisions. As of November 2006, the measurement disagrees with the Standard Model by 3.4 standard deviations,[6] suggesting beyond the Standard Model physics may be having an effect (or theoretical/experimental errors not completely under control).



One-loop MSSM corrections to the muon g-2 involving a neutralino and a smuon, and a chargino and a muon sneutrino respectively.

The E821 experiment at Brookhaven National Laboratory (BNL) studied the precession of muon and anti-muon in a constant external magnetic field as they circulated in a confining storage ring. The E821 Experiment reported the following average value (from the July 2009 review by Particle Data Group)

$$a = \frac{g-2}{2} = 0.00116592089(54)(33)$$

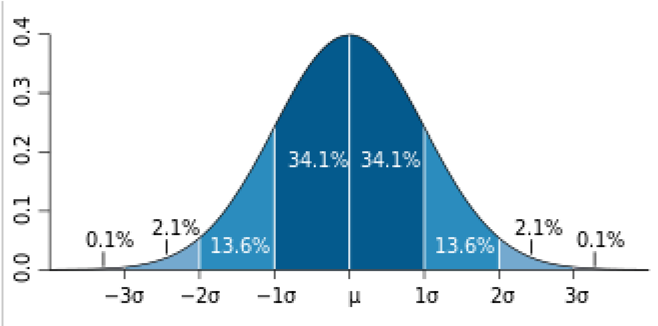
where the first errors are statistical and the second systematic.

The anomolous magnetic moment and g-2

- g≈2 but higher-order corrections
  - QED, EW, hadronic, new physics?

$$\vec{\mu} = g_s \left(\frac{q}{2m} \right) \vec{s}$$

- Most recent measurement of g-2 at Brookhaven National Lab found ~3σ discrepancy between theory and experiment
- New muon g-2 experiment at Fermilab expected precision could yield ~5σ



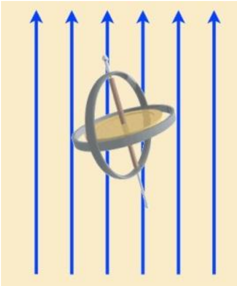
Dark blue is less than one standard deviation away from the mean. For the normal distribution, this accounts for 68.2% of the set, while two standard deviations from the mean (medium and dark blue) account for 95.4%, and three standard deviations (light, medium, and dark blue) account for 99.7%.

http://en.wikipedia.org/wiki/Normal_distribution

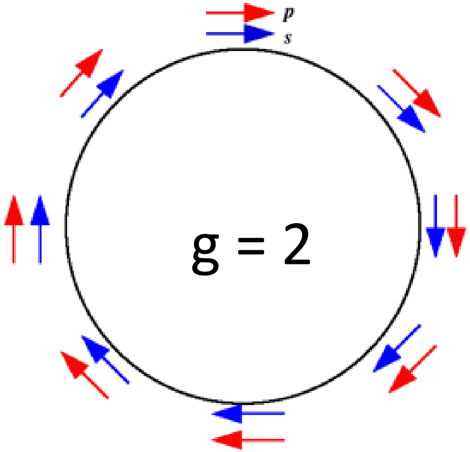
Measuring g-2

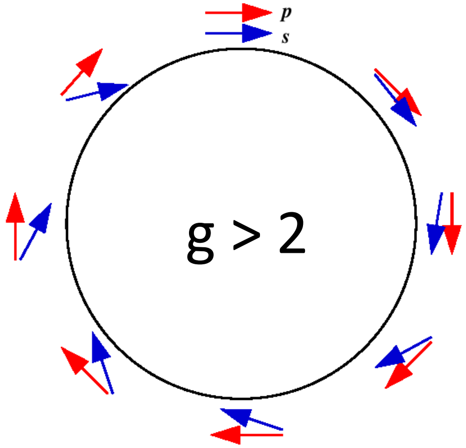
- Polarized muons in magnetic field precess with Larmor spin precession frequency

$$\vec{\omega}_s = -\frac{eB}{\gamma mc} - \frac{e}{mc} a\vec{B} \qquad a = \frac{g-2}{2}$$



- Measure g-2 using cyclotron





$$\vec{\omega}_c = -\frac{e\vec{B}}{\gamma mc}$$

$$\vec{\omega}_a = \vec{\omega}_s - \vec{\omega}_c = -\frac{e\vec{B}}{2mc}(g-2)$$

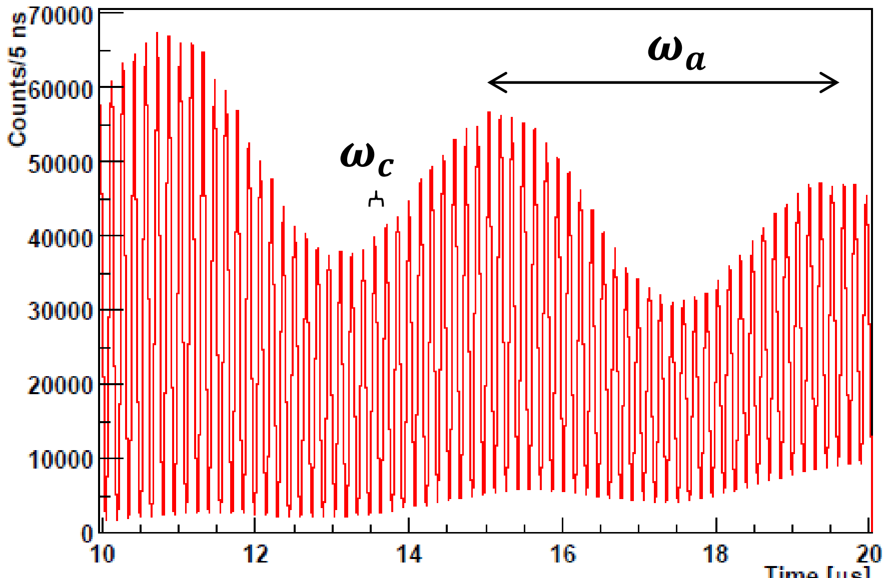
- Requires precise measurements of ω_a and of the magnetic field

Measuring ω_a

- One more trick:
  - Polarized muons in storage ring with vertical focusing by electrical quadrupole field

$$\vec{\omega}_a = -\frac{e}{mc}\left[a\vec{B} - \left(a - \frac{1}{\gamma^2 - 1}\right)\vec{\beta} \times \vec{E}\right]$$

  - At magic momentum p_μ = 3.094 GeV/c (γ = 29.3), g-2 precession frequency ω_a independent of electric field
- Distribution of decay electrons as function of time

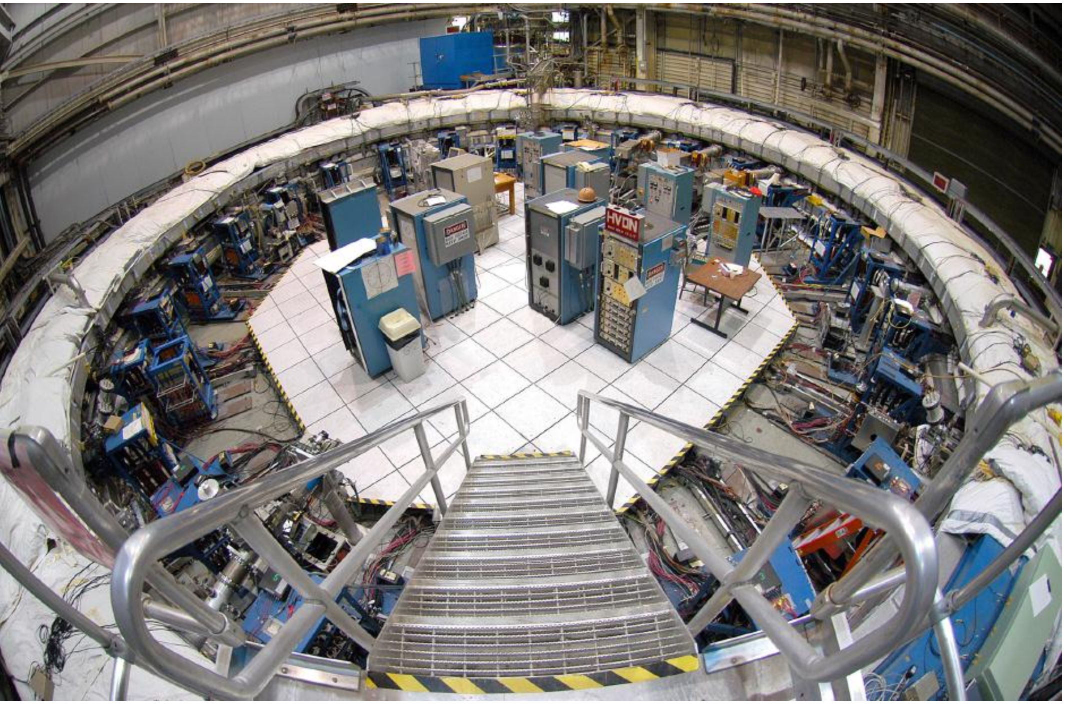


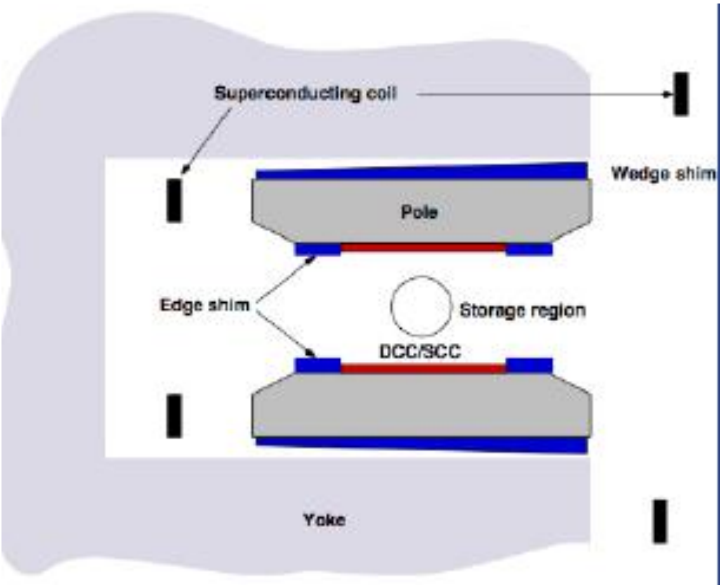
$$N(t) = N_0 e^{-t/\gamma\tau}[1 - A\cos(\omega_a t + \varphi)]$$

Intensity at a single detector station shortly after injection
Phys. Rev. D73 (2006) 072003

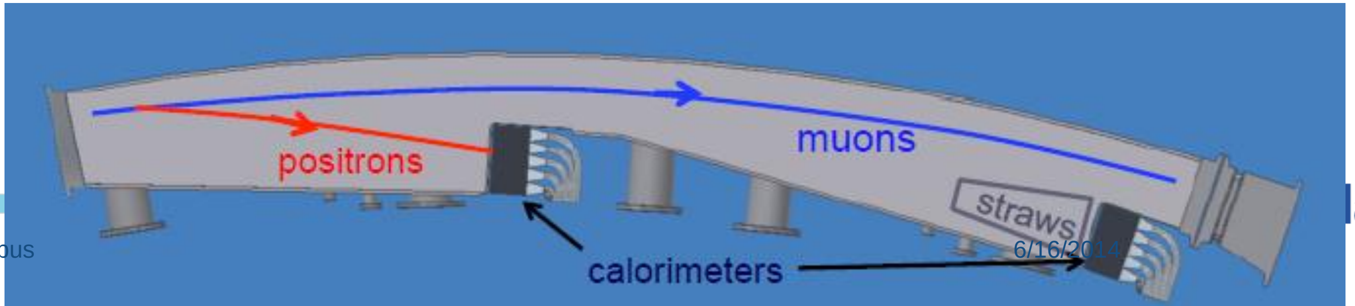
g-2 apparatus

- Reusing storage ring from BNL g-2 experiment



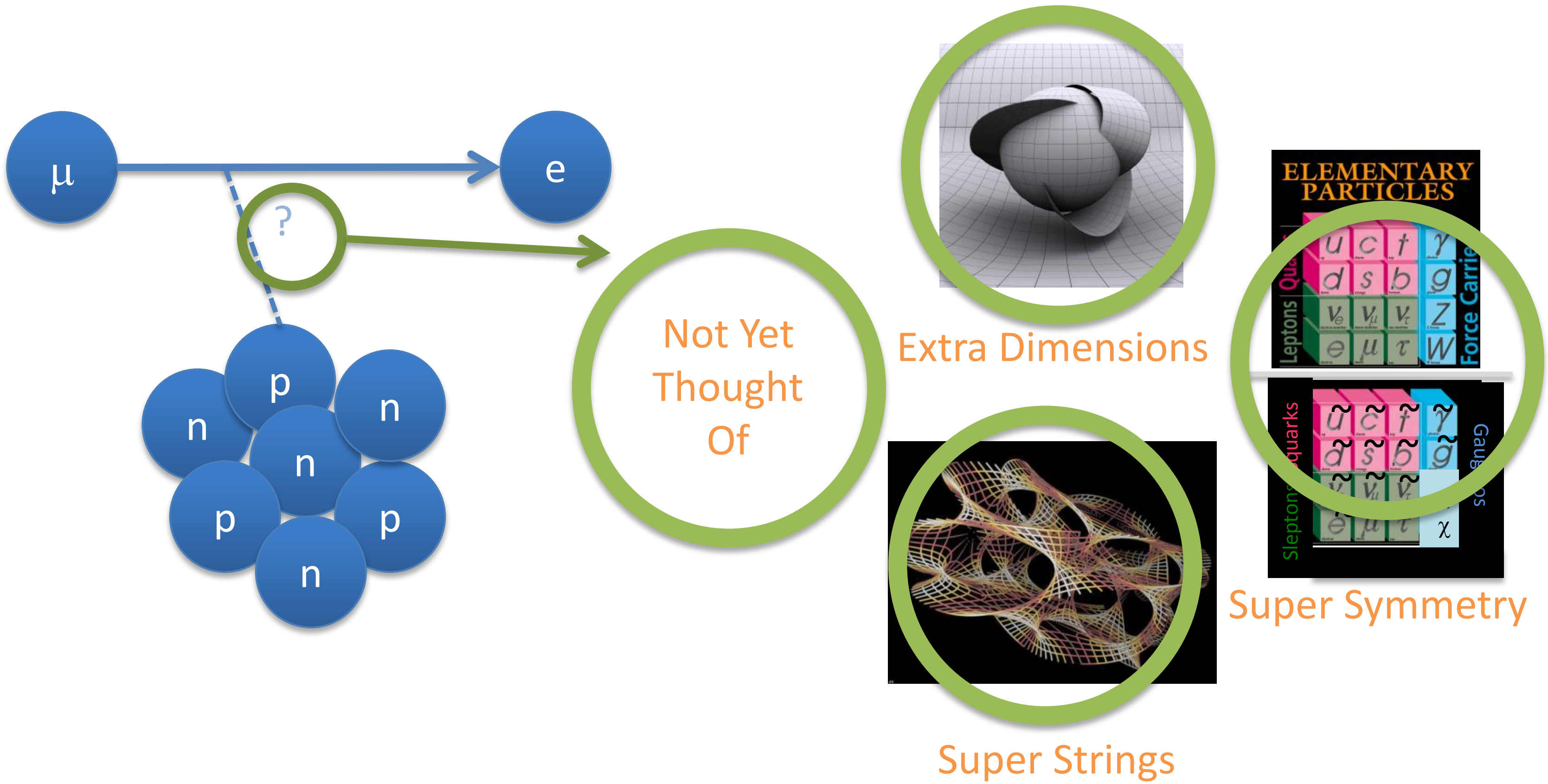


- New calorimeters and straw-tube tracking



Mu2e

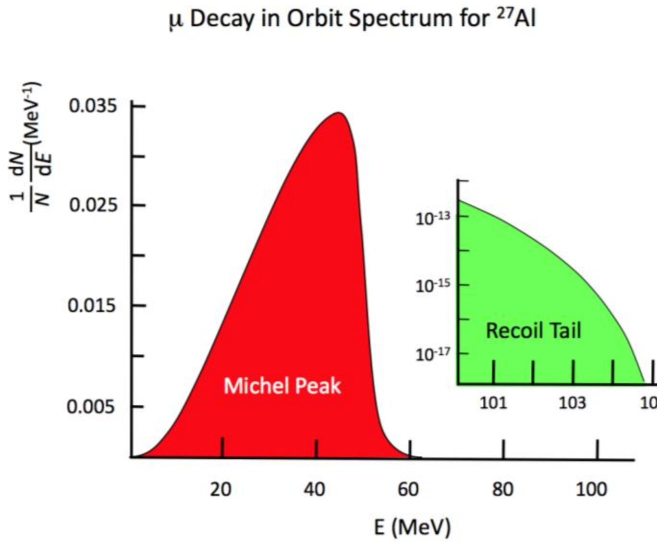
- Muons regularly decay to electrons and neutrinos $\mu^- \rightarrow e^- \nu_e \bar{\nu}_\mu$
- Mu2e will search for charged lepton flavor violation ($\mu N \rightarrow eN$)
  - Neutrino flavor oscillations already observed



- Conversion rate distinguishes between different theories

Mu2e

- Generate beam of low-momentum μ^-
- Stop the muons in a target
  - Aim to improve sensitivity by 10^4 over previous experiments
  - requires ~10^{18} stopped muons
- Stopped muons are trapped in orbit around the nucleus
  - Look for conversion of muon to electron
    - conversion-electron energy 104.97 MeV
    - (maximum decay-e energy 52.8 MeV)



Mu2e

Steve Werkema

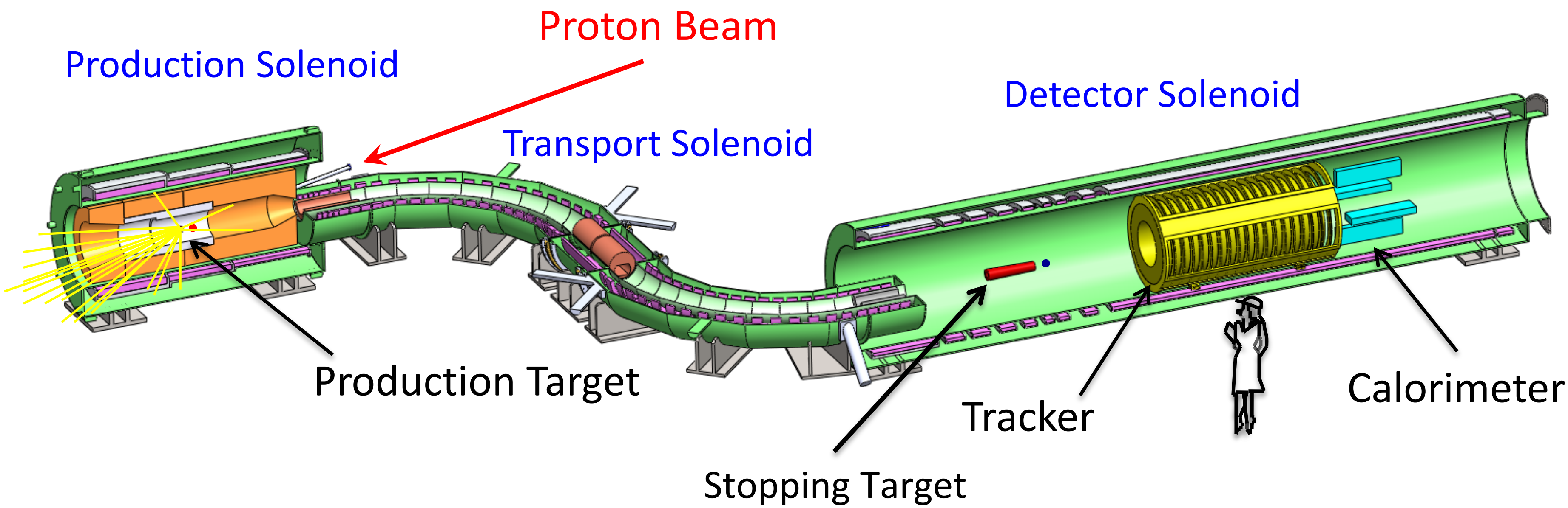
Production Solenoid
- Production target
- Graded field
- π's → μ's

Transport Solenoid
- Transport muons to stopping target
- Collimation system selects muon charge and momentum
- Pbar window in middle of central collimator

- ~ 0.0016 stopped μ^-/POT
- 10^{10} Hz of stopped muons

Detector Solenoid
- Muon stopping target (Al)
- Tracker
- Calorimeter

The signal is the response of the Tracker and the Calorimeter to the passage of the conversion electron.



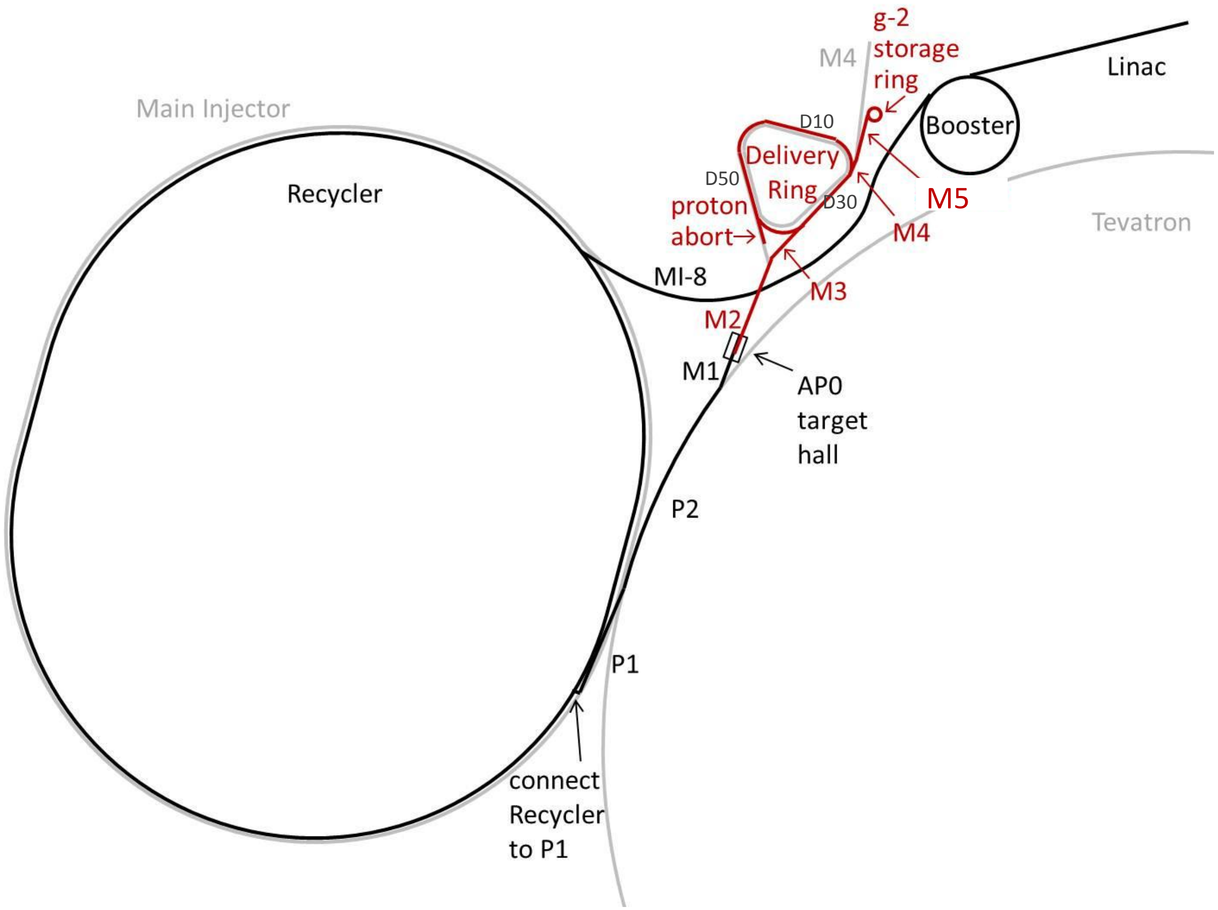
Fermilab

Muon Campus infrastructure

- Reusing beam enclosures that were used to make antiprotons for the Tevatron proton-antiproton collider
- Beamline from Main Injector / Recycler to Target Station
- Beamlines from Target Station (or bypass) to “Delivery” Ring (former antiproton Debuncher)
- Former Antiproton Accumulator ring being scrapped for parts
- Building new tunnel and beamlines from Delivery Ring to experiments
- New building for Mu2e
- MC-1 building already constructed to house g-2, cryogenic plant and beamline power supplies for both experiments

Path of beam to Muon Campus

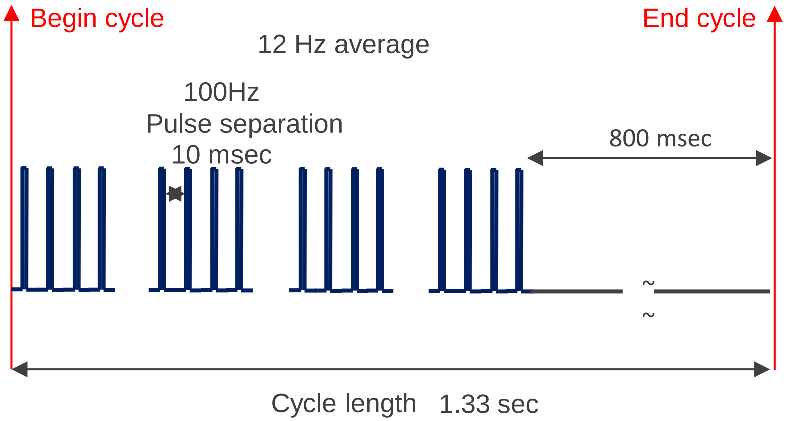
- Protons accelerated in Linac and Booster to 8 GeV and then transferred to Recycler



Fermilab

Path of beam to Muon Campus

- Bunches of $4x10^{12}$ protons rebunched in the Recycler using 2.5 MHz RF into 4 bunches of 10^{12} protons with bunch length ~120ns and extracted with 10ms spacing



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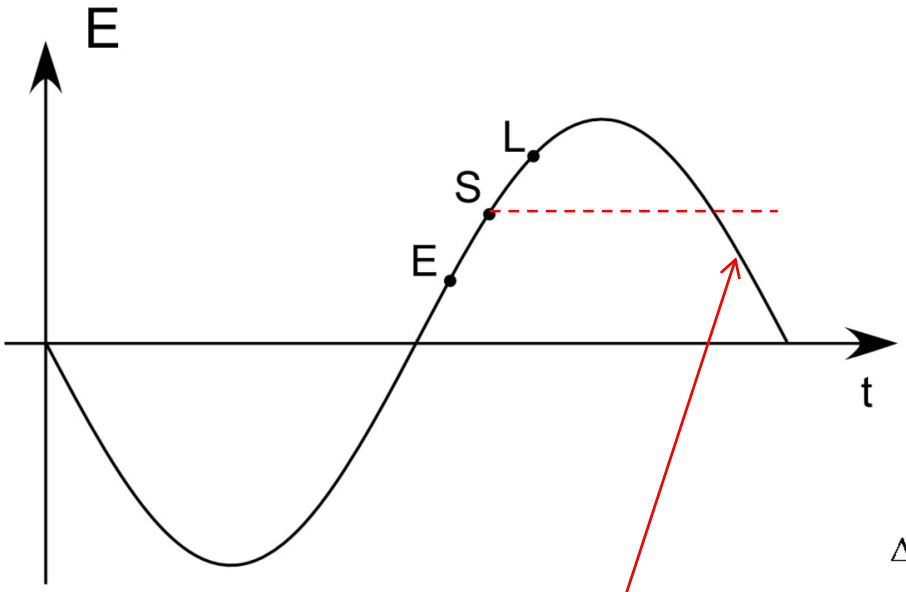
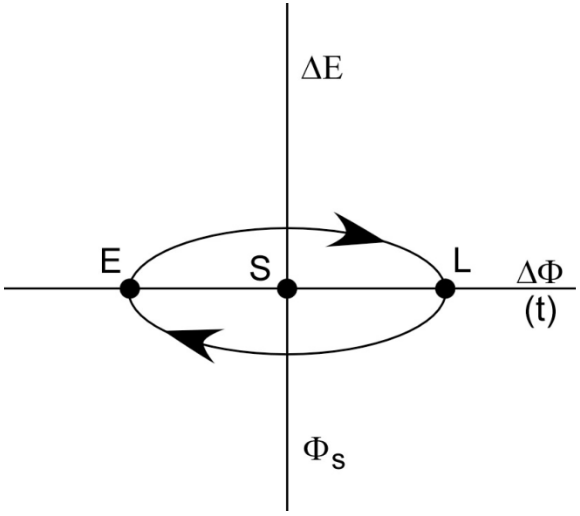
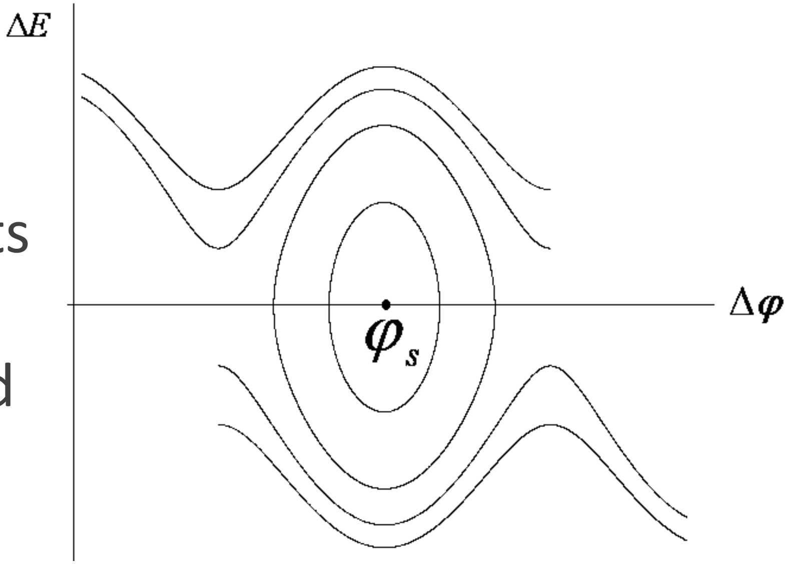
Aside on bunching beam using RF





particle here is late and gets less kick than synchronous particle, so gets farther and farther behind (unstable)



Coalescing

- Make one large bunch of beam out of many smaller bunches using 2 sets of RF with different frequencies
- Used for beam injected into Tevatron

Bunches circulating around MI, captured by RF with frequency 53 MHz and voltage 1.1 MV
Bunch shape matches to the 1.1 MV RF bucket

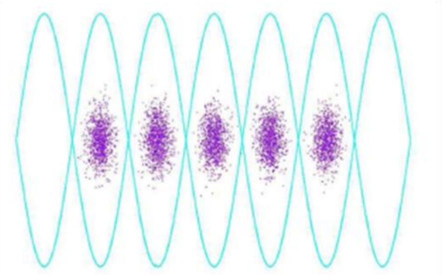


Figure 2 Bunch coalescing. Step 1

53 MHz RF → 0 V and 2.5 MHz RF → 75 kV
Bunches start rotating in 2.5 MHz bucket until bunch length minimum

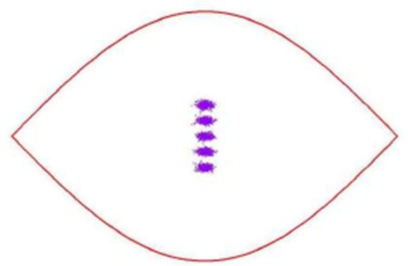


Figure 4 Bunch coalescing. Step 3

Decrease voltage suddenly so bunches start rotating in phase space until energy spread is minimum

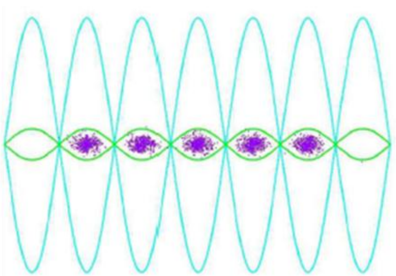


Figure 3 Bunch coalescing. Step 2

2.5 MHz RF → 0 V and 53 MHz RF → 1.1 MV and captures the coalesced bunch

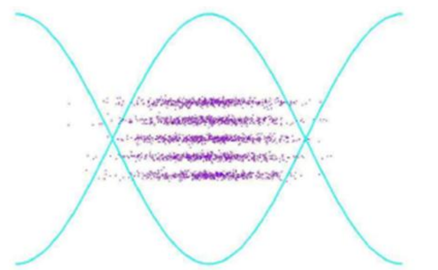
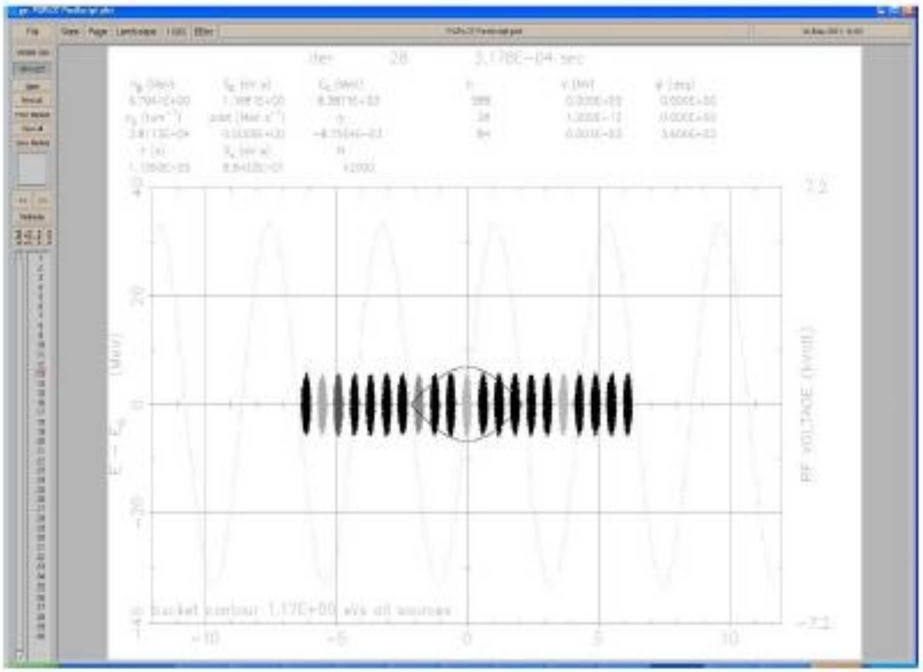
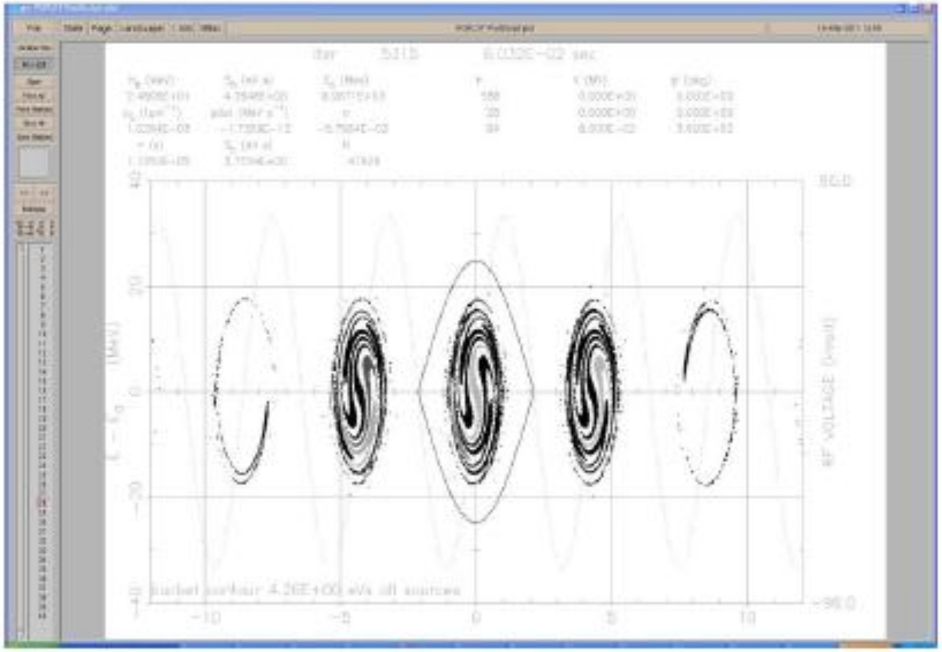


Figure 5 Bunch coalescing. Step 4

Rebunching beam in Recycler for Muon Campus

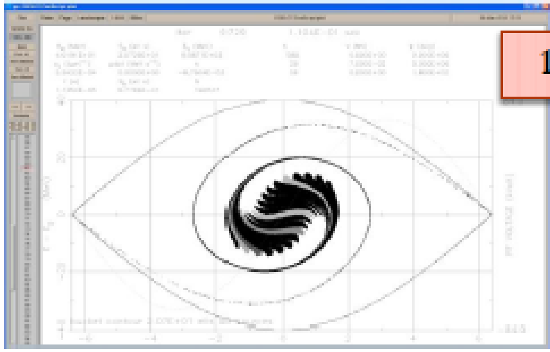
- Only room for single RF system besides the 53 MHz RF
- Raise voltage of lower frequency RF system adiabatically

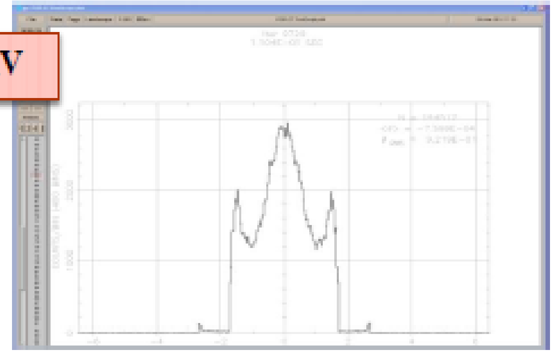




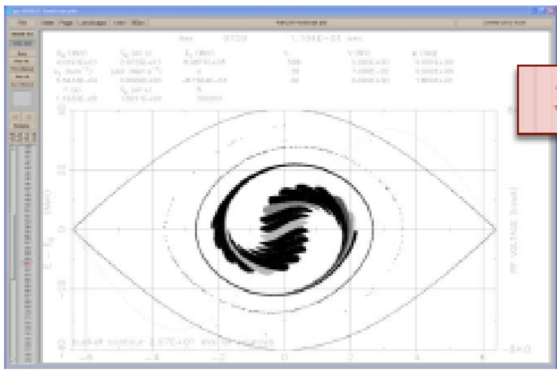
Effect of the initial 2.5 MHz voltage

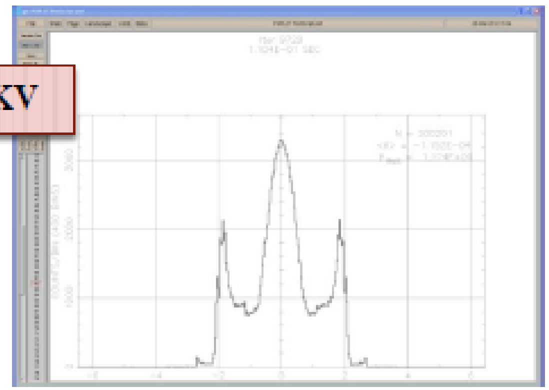
1 KV



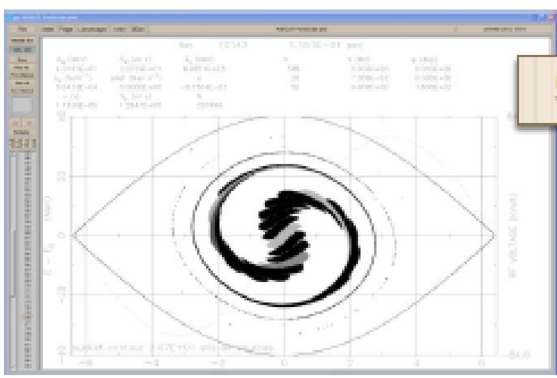


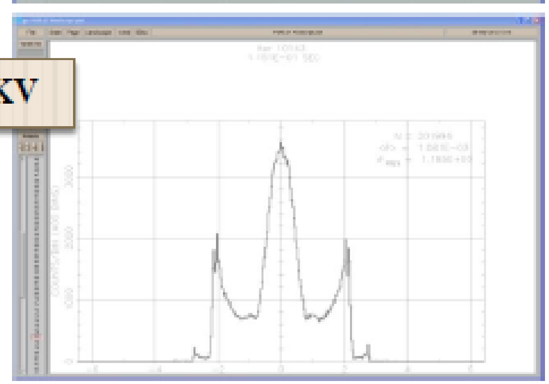
3 KV





5 KV

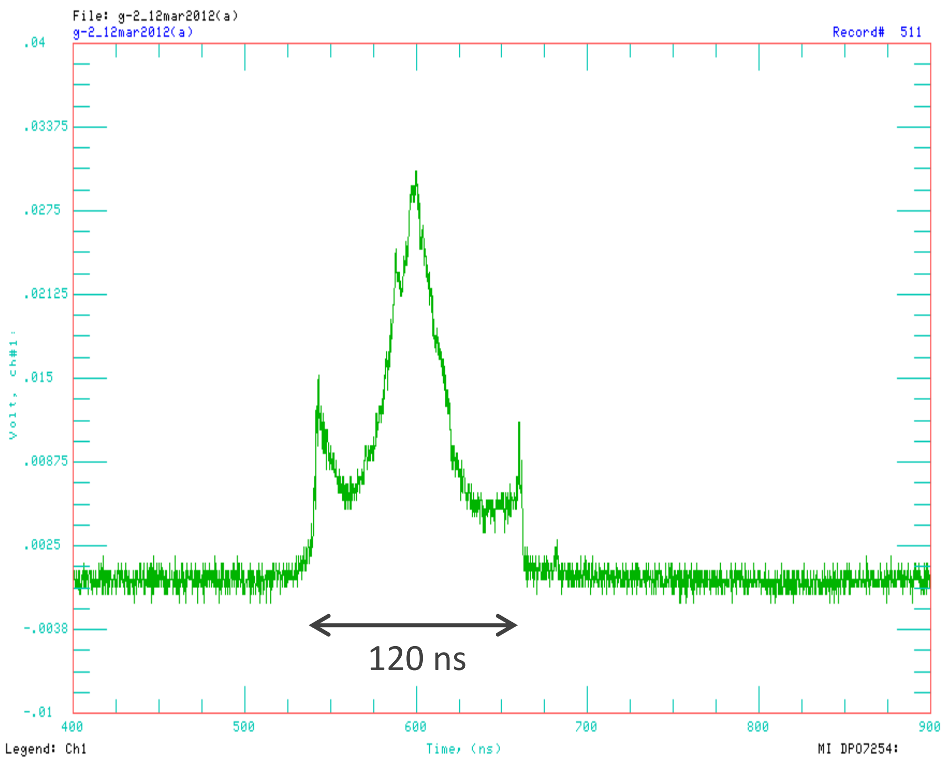




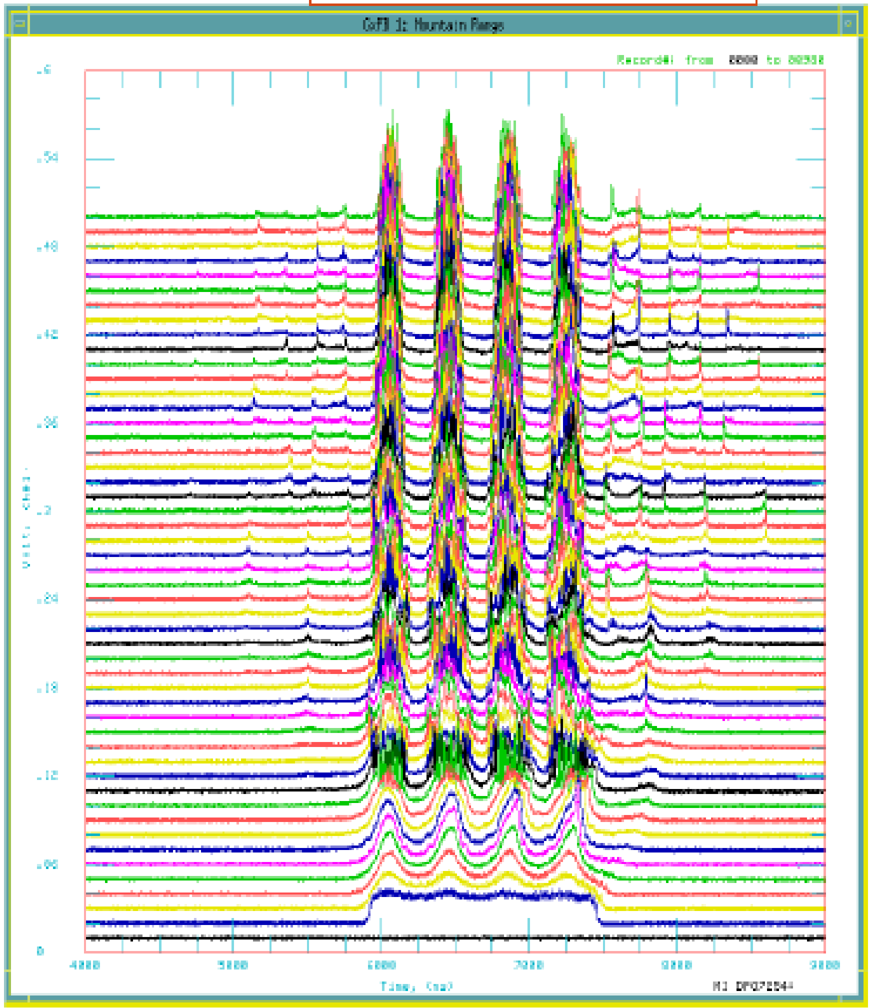
Initial 2.5 MHz Voltage (KV)	Overall Efficiency (%)	Fraction of Beam within 120 nsec (%)
1	92.6	99.2
3	95.3	94.7
5	96.2	92.3

Beam studies using Main-Injector coalescing cavities

- Good agreement with simulations

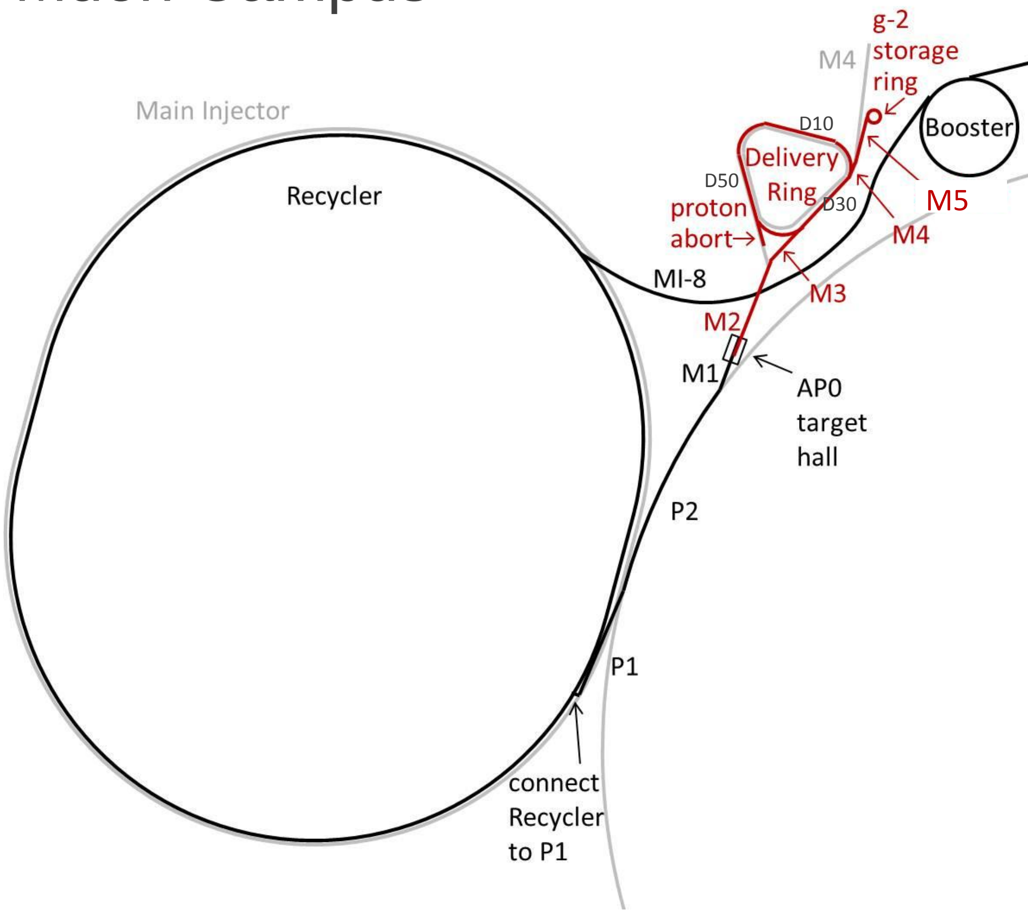


W. Chou et al



Path of beam to Muon Campus (continued)

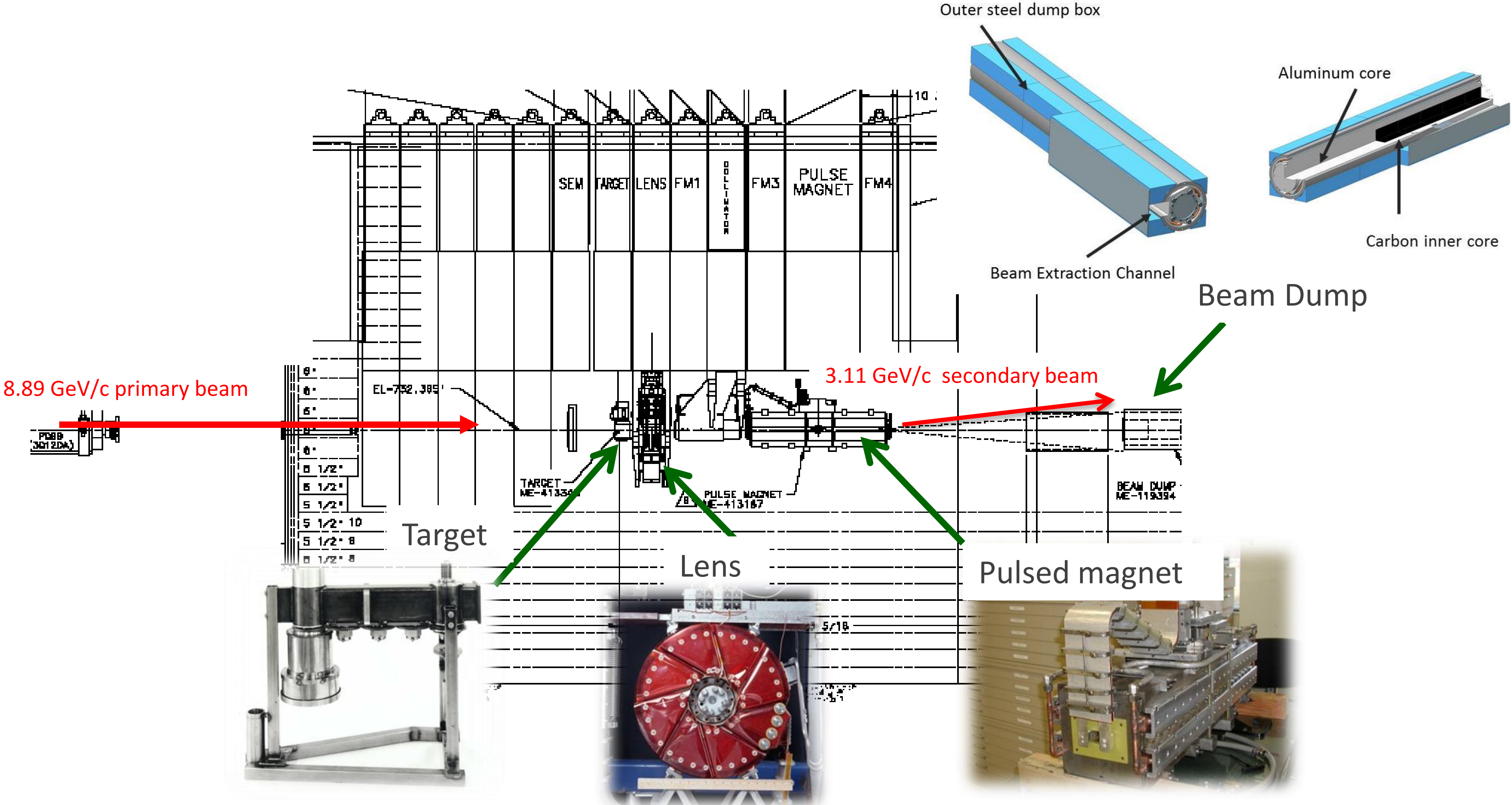
- 8-GeV protons from the Recycler are transferred down the P1, P2, and M1 lines to the Muon Campus
- For g-2, the protons hit a target at AP0; the particles created from beam hitting the target ("secondary beam") continue down the M2 and M3 lines to the Delivery Ring
- For Mu2e, the 8-GeV protons bypass the target and continue down the M3 line to the Delivery Ring



Fermilab

g-2 target station

- Used for antiproton production for the Tevatron collider

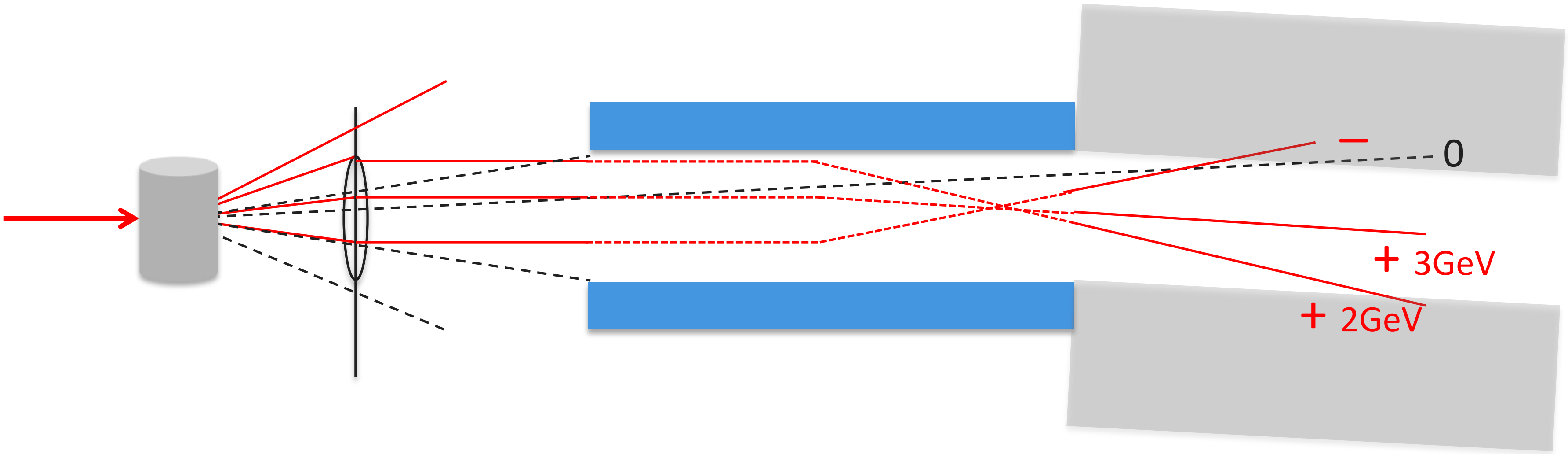


How do we create a muon beam?

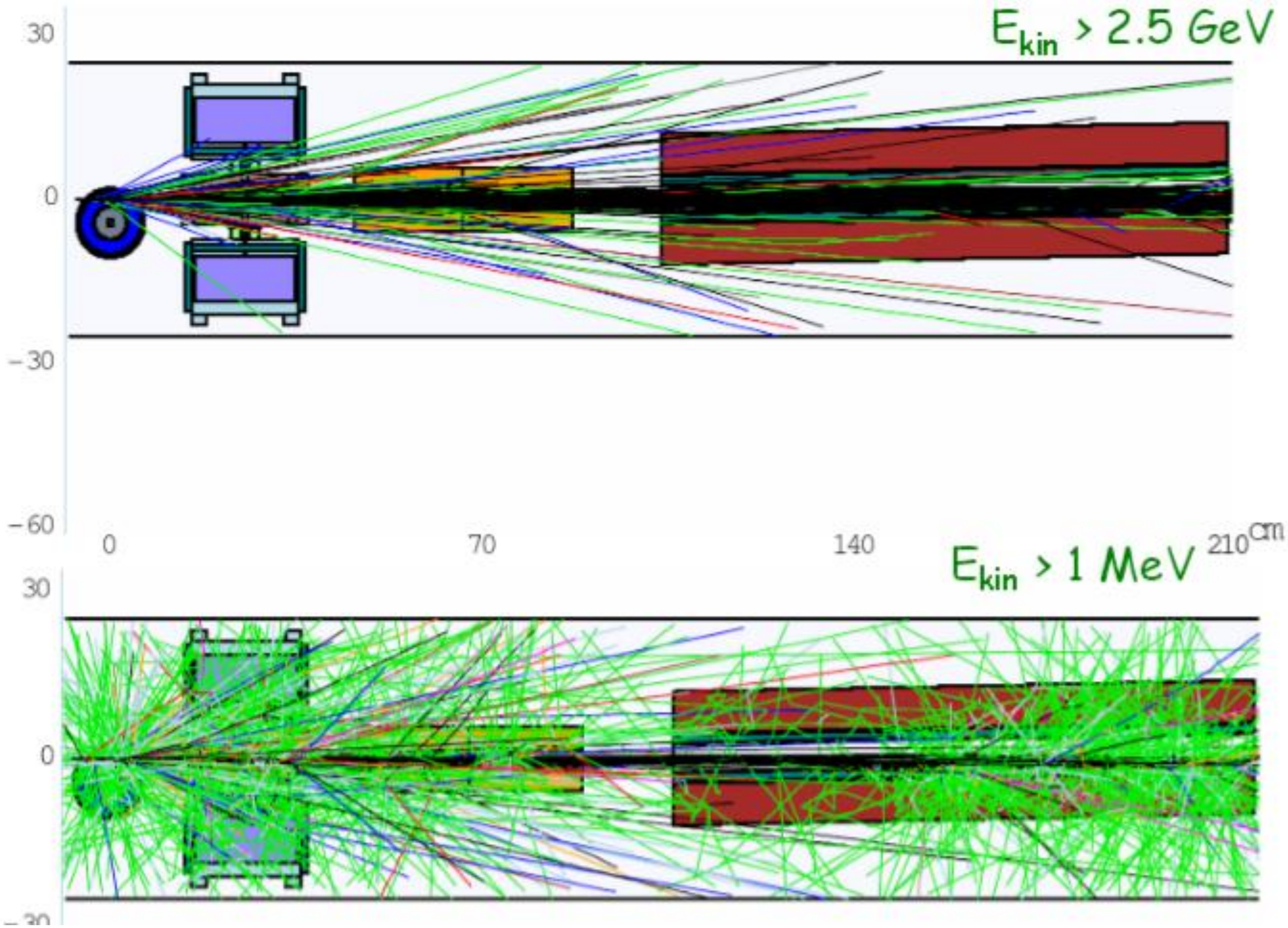
- We start by slamming a beam of protons with 8 GeV/c momentum onto a target
  - 8 GeV beam is what we have available
  - Higher energy would have produced more particles, or a higher-intensity muon beam
- Particles of many types and momenta are created consistent with conservation of energy

How do we create a muon beam?

- The “secondary” beam is focused to retain as many particles as possible
- A dipole magnetic field is used to select the desired charge and momentum of particles in the secondary beam

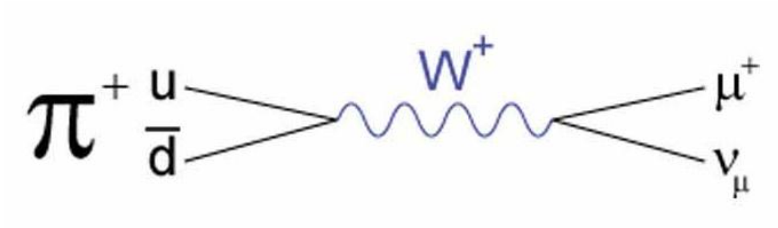


Simulation showing secondary particles in g-2 target station

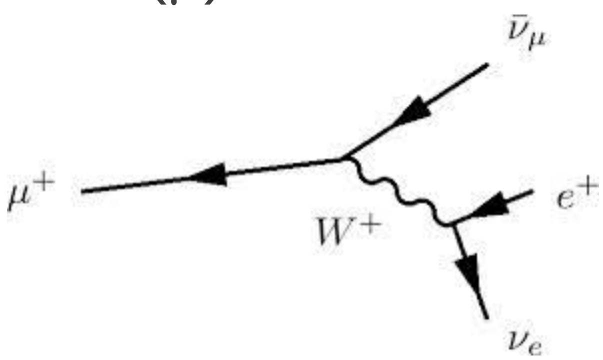


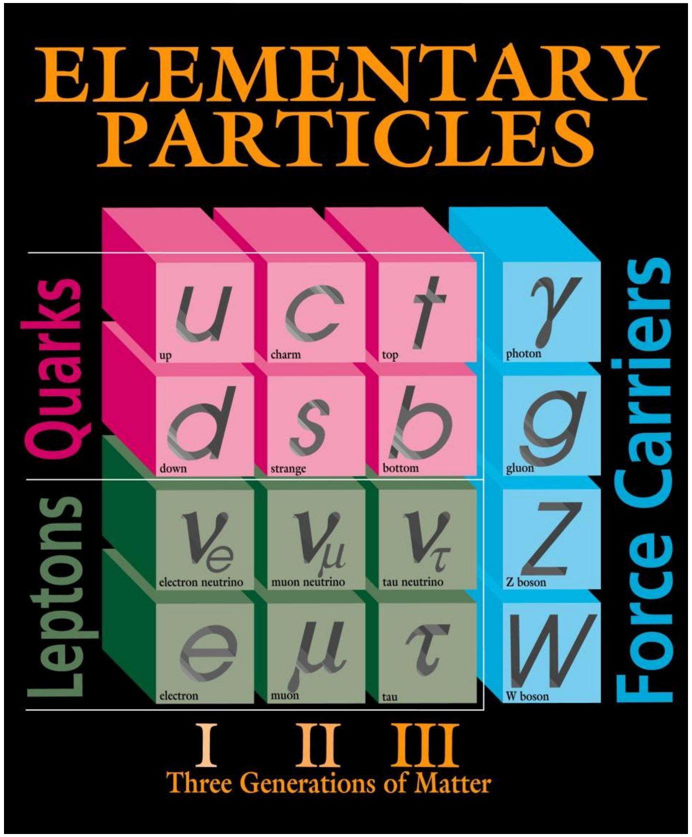
Particle decay

- Electrons (e) and protons (p=uud) are stable
- Heavier particles decay down to these particles (plus neutrinos (ν))
- For example pions $\pi^+=u\bar{d}$



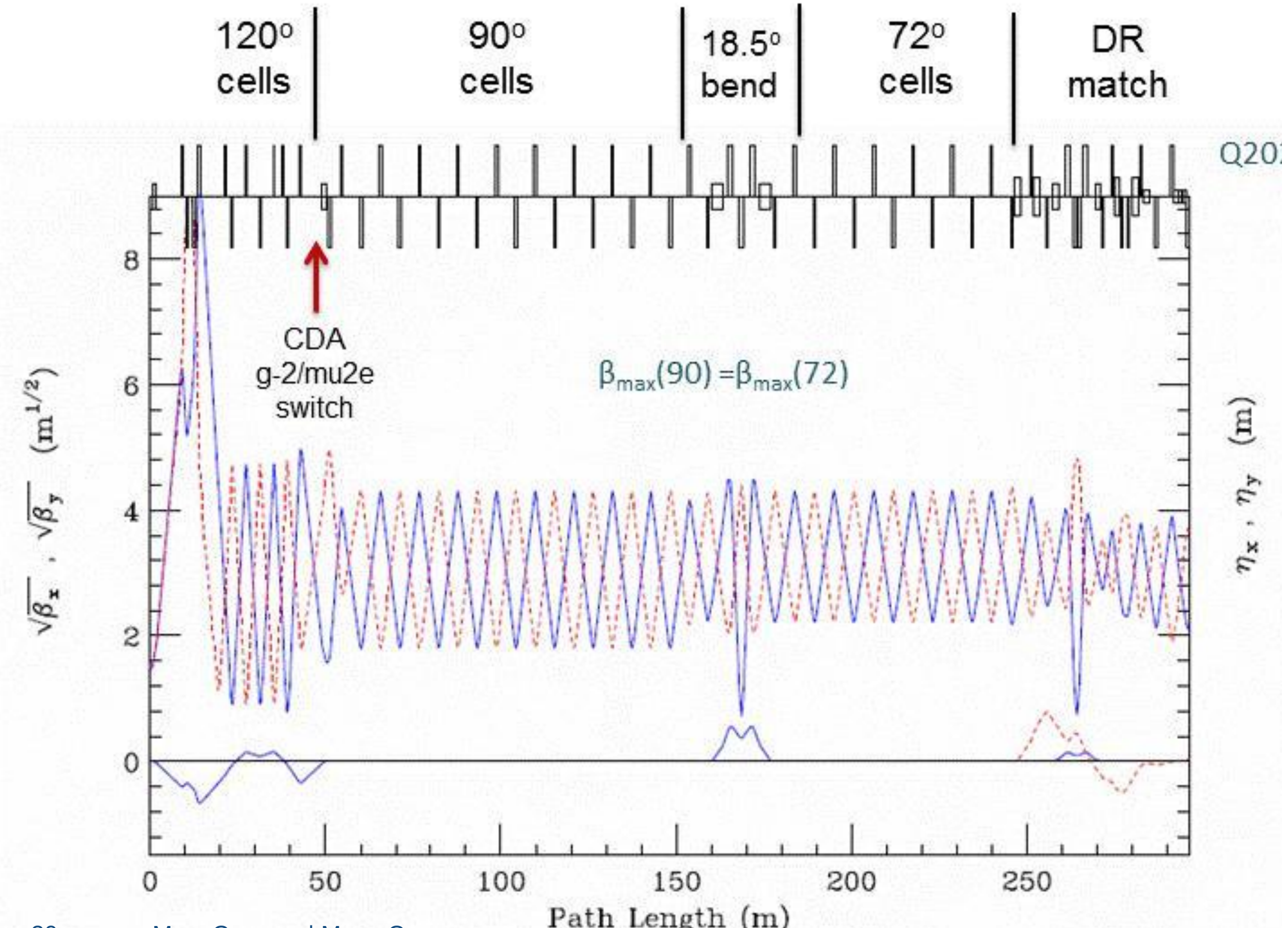
- and muons (μ)

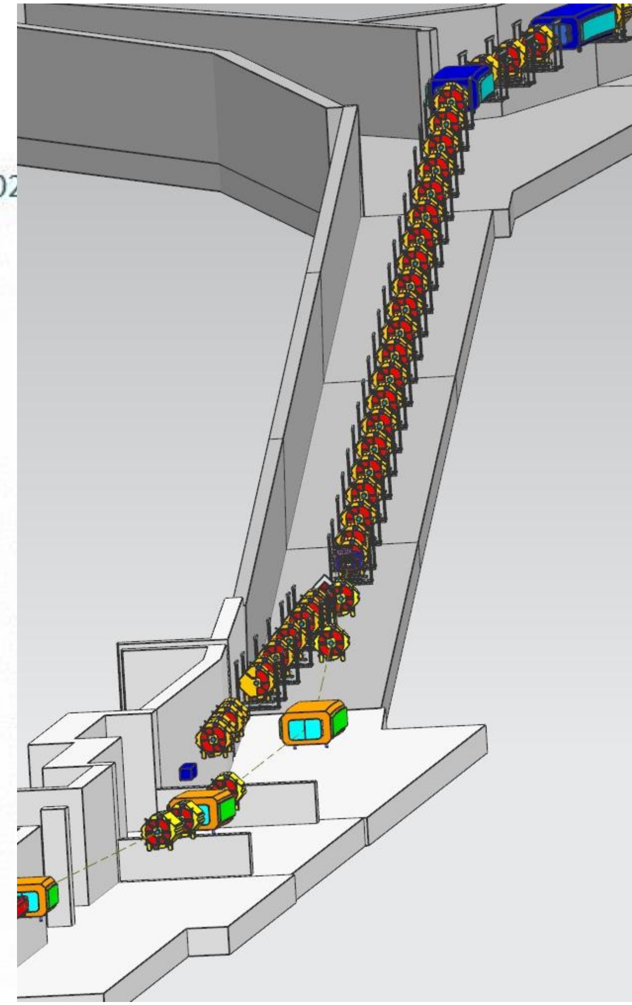




g-2 pion decay beamlines (M2,M3)

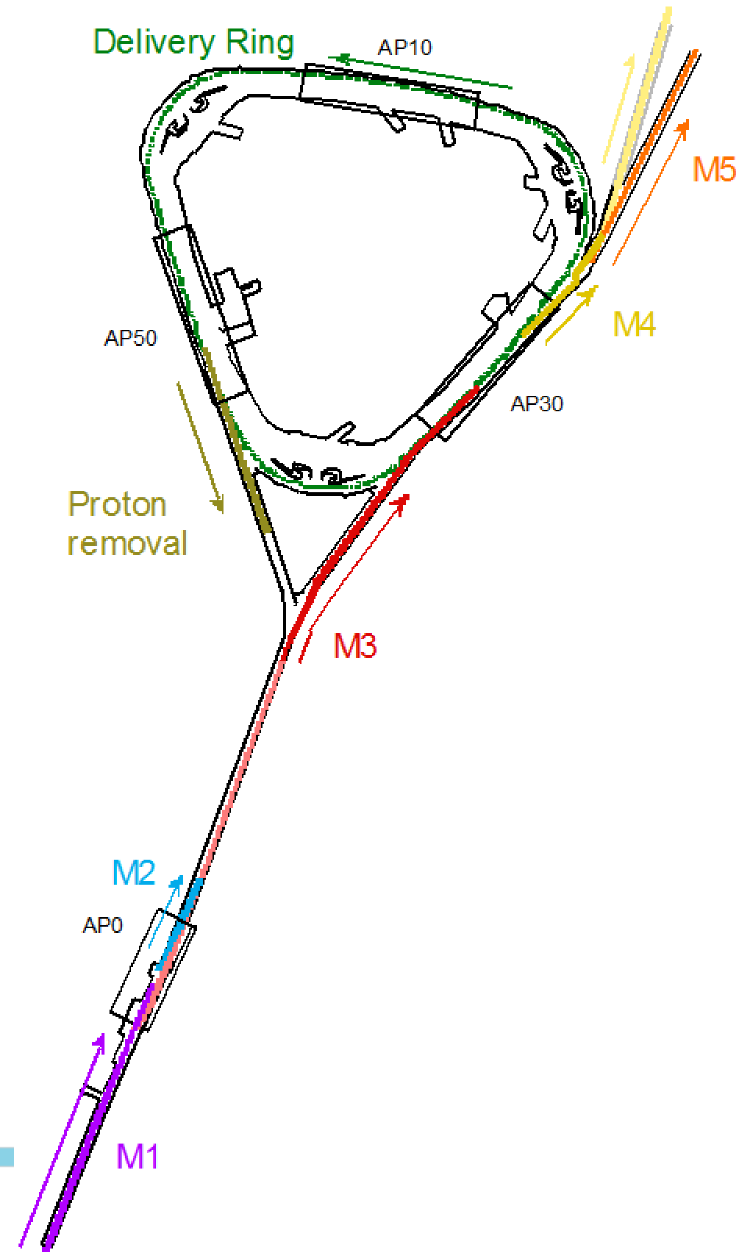
- Beta functions kept low to capture as many decay μ's as possible
- Quad density ~tripled in FODO region compared to use during antiproton production





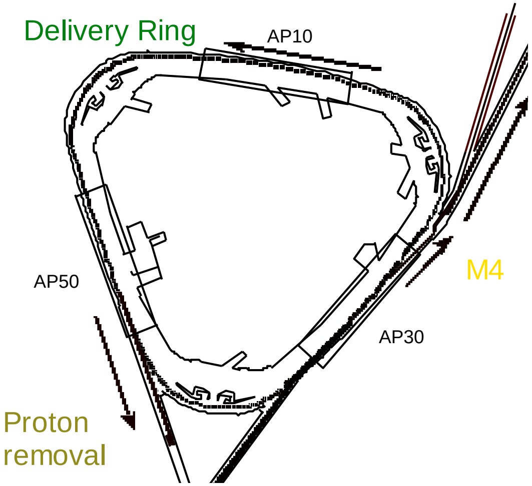
g-2 secondary beam in the Delivery Ring

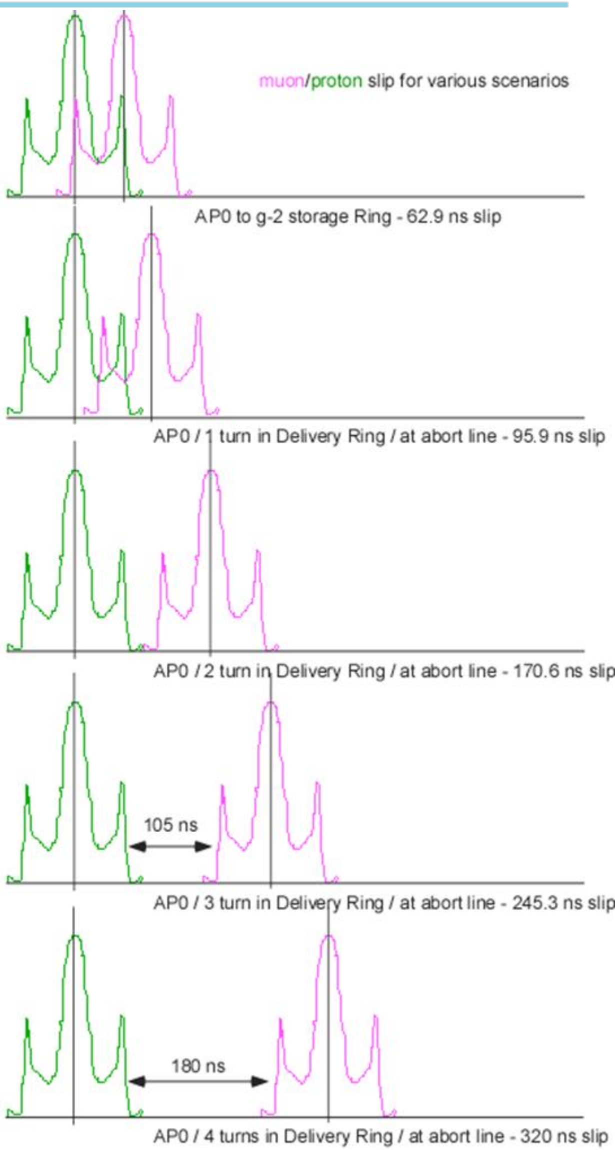
- By the time the beam reaches the Delivery Ring, only particles remaining are p, e^+, μ^+, and 28% of the original π^+
- After 1 loop around Delivery Ring, 99% of π^+ have decayed
- When π^+ decay into μ^+, the muons may not have momentum which is accepted by the beamline – we capture <1% of muons from decays
- Beam in the Delivery Ring is ~99% p and ~1% μ^+



g-2 proton removal in the Delivery Ring

- So we have 10^7 p and 10^5 μ^+ in the Delivery Ring
- The momentum of the beam is 3.1 GeV but the protons are heavier than the muons, so they are slower
- After 3-4 turns around the Delivery Ring, the protons lag behind the muons enough that we can let the muons pass by and then kick the protons out
- More than 90% of μ^+ make it to the g-2 ring before they decay into e^+





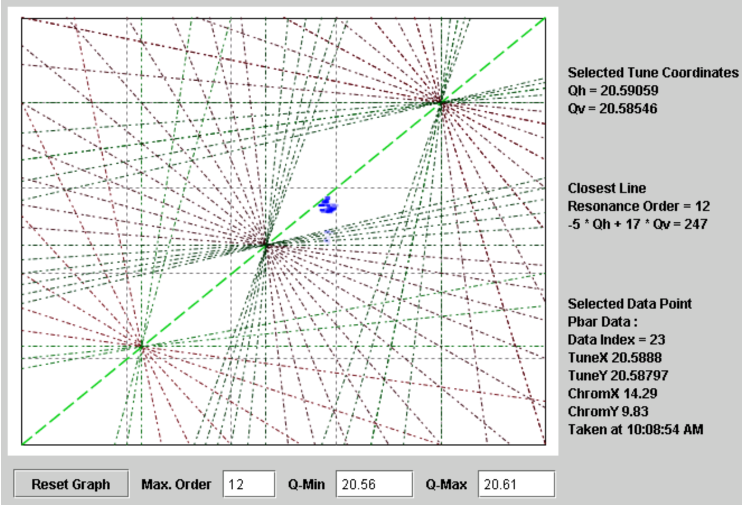
Mu2e slow spill using resonant extraction

- Mu2e 8-GeV protons bypass the g-2 target and continue to the Delivery Ring
- Don't want full intensity in single pulse to the target/detector
- Bunches in Delivery Ring circulate with revolution frequency of 1.686μs
- Beam "spills" out of ring over thousands of revolutions (54ms) using resonant extraction

Aside on resonances

- In storage ring, don't want beam to come back to same place in phase space every revolution or every n revolutions
- $nQ=p$ or $nQ_h+mQ_v=p$
- If there were an imperfection at some location, it would disturb the beam each time it passed, eventually driving the beam out of the machine
- For resonant extraction, intentionally tune to resonance to drive beam out of the machine in a controlled way

Tevatron tune diagram

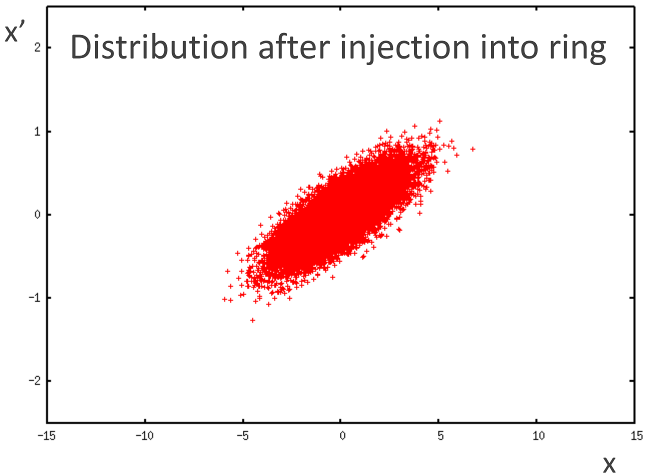


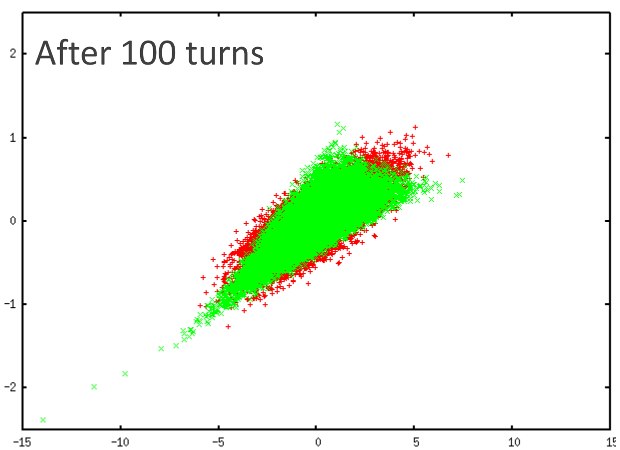
Choose "working point" away from resonance lines

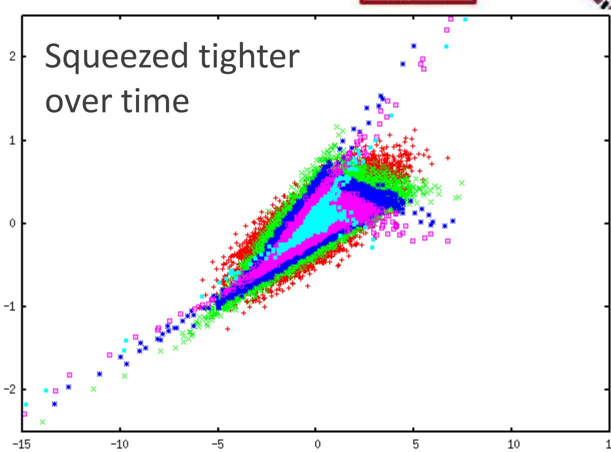
Mu2e resonant extraction

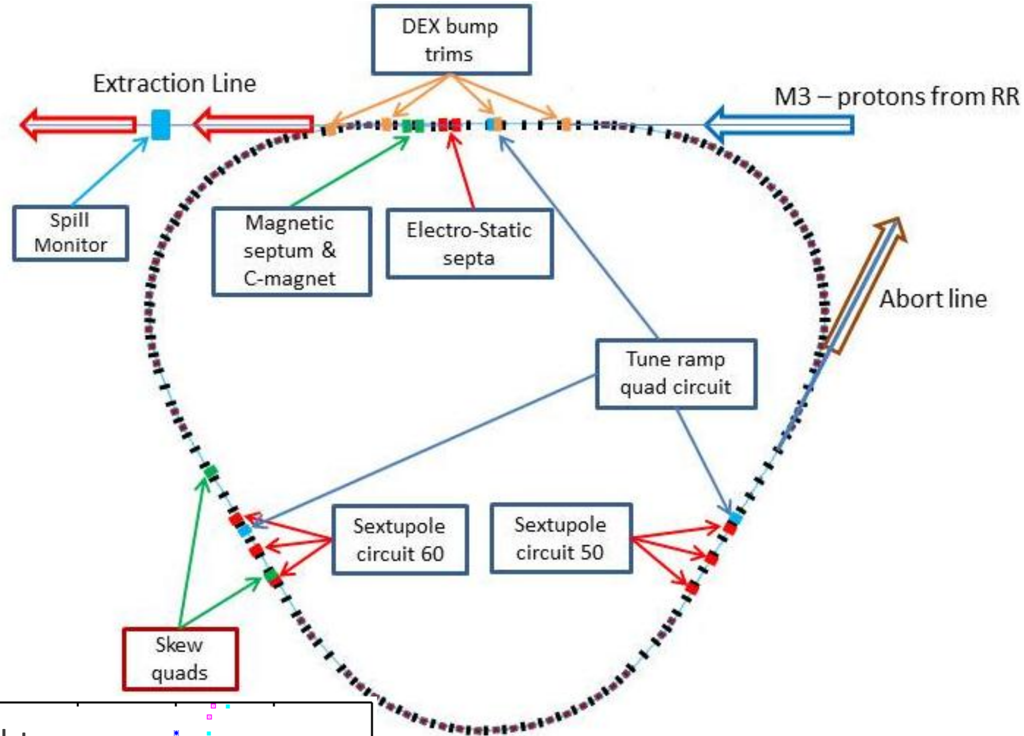
(3Q=p)

- Third-integer resonance driven by sextupole field





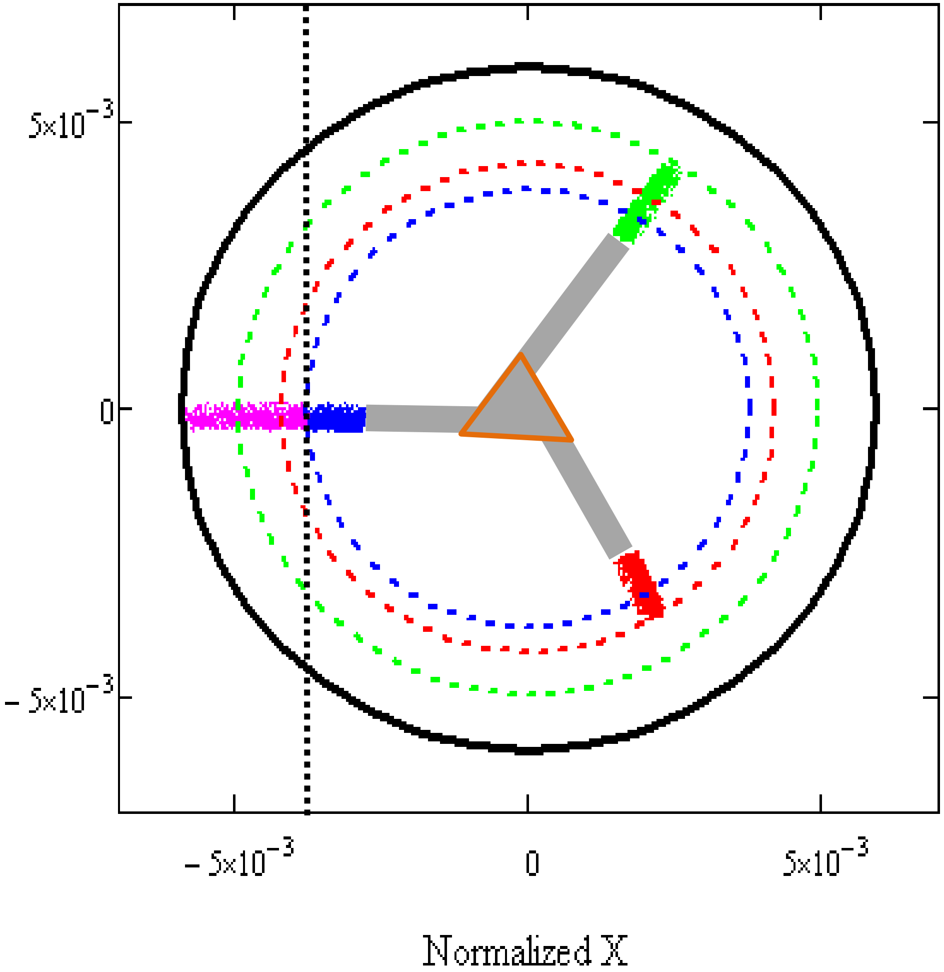




Fermilab

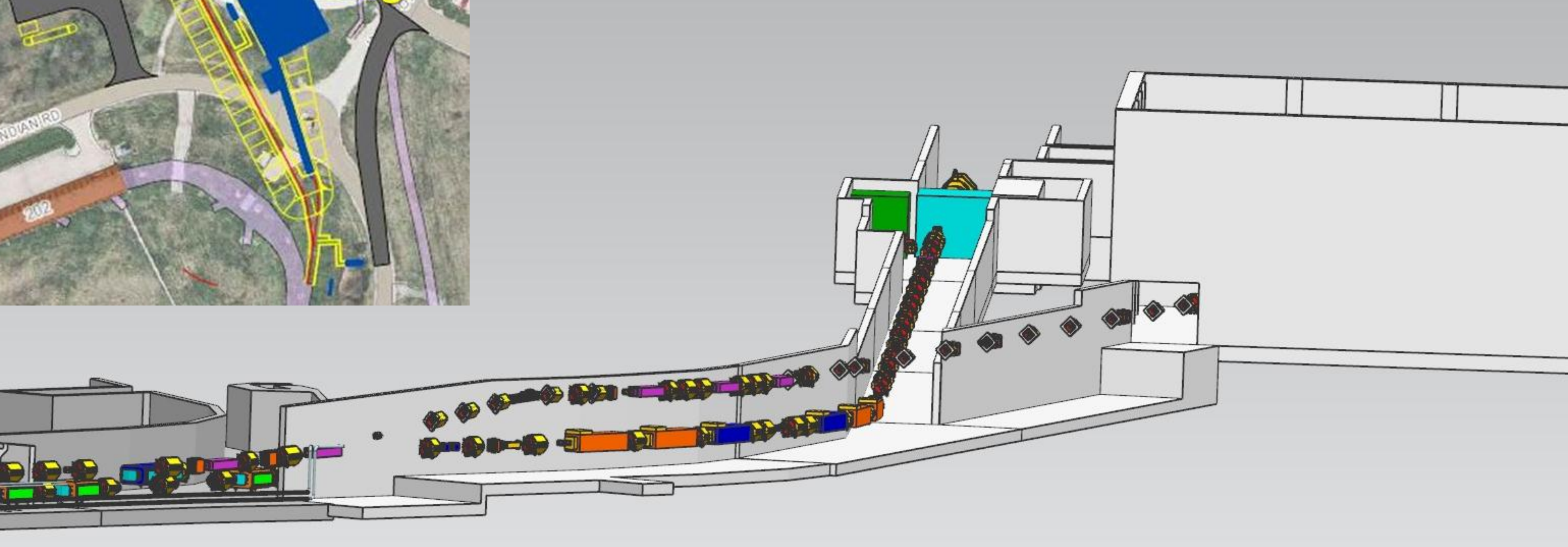
Mu2e resonant extraction

- Electrostatic septum steers displaced beam to extraction line



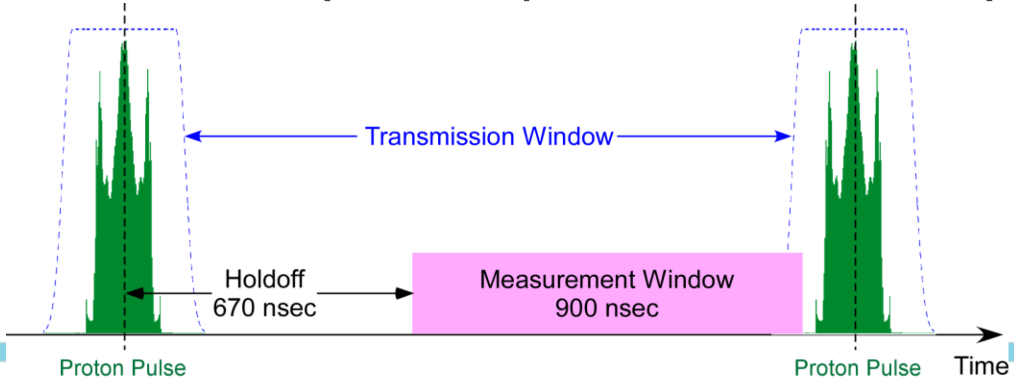
Beam from Delivery Ring to Mu2e/g-2 (M4/M5 line)

- g-2 steer beam, optimize injection into ring
- Mu2e steer beam towards experiment, extinction/collimation, diagnostic absorber, final focus on target



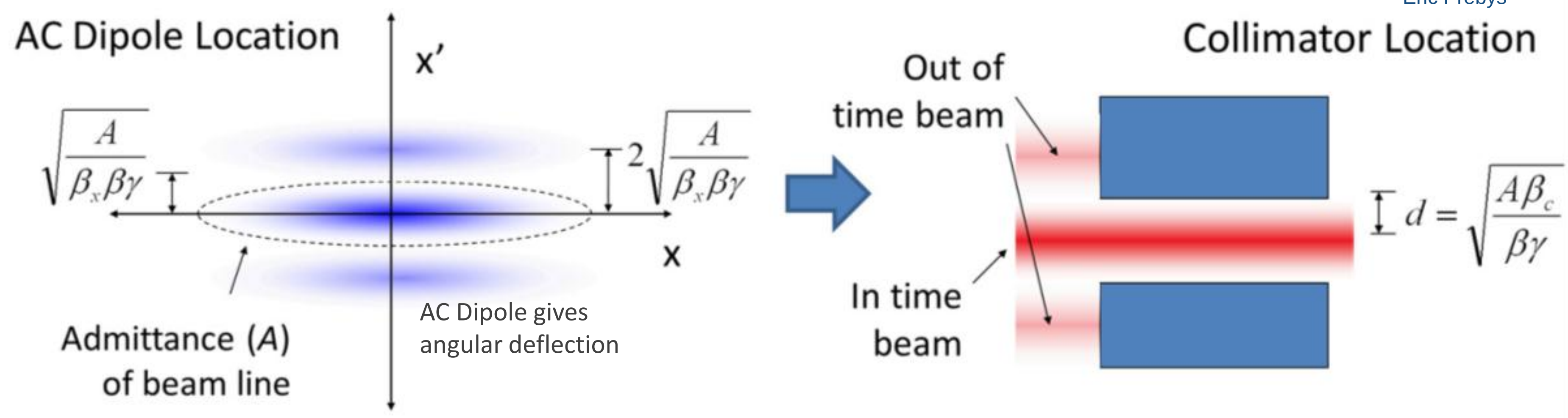
Mu2e extinction

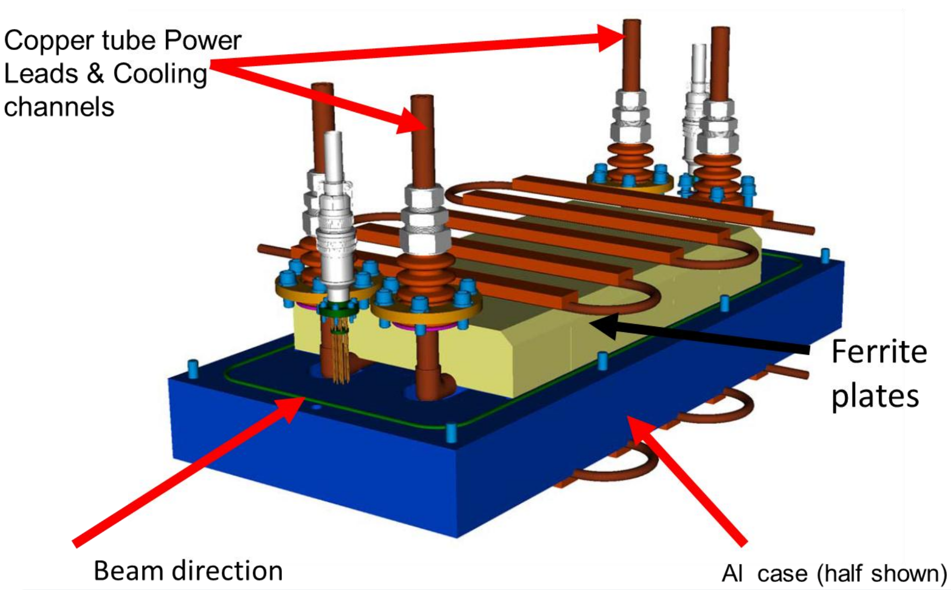
- Signal is electron with energy 105 MeV ($\approx M_\mu$)
- Many backgrounds produce prompt electron (very soon after proton hits target) which could be 105 MeV
- If all protons in a pulse hit the target at the same time, could just wait till prompt background passed
- 95% of protons are within 120ns window
- Use Extinction device to remove protons outside of $\pm$125 ns
- Beam outside of $\pm$125 ns window must be extinguished to a level of 1 out-of-time proton per 10^{10} in-time protons

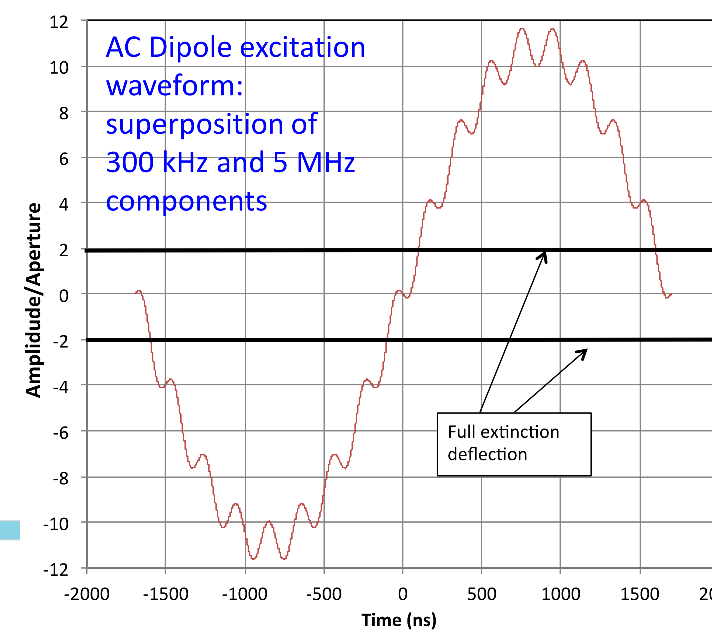


Extinction of out-of-time beam using AC dipole

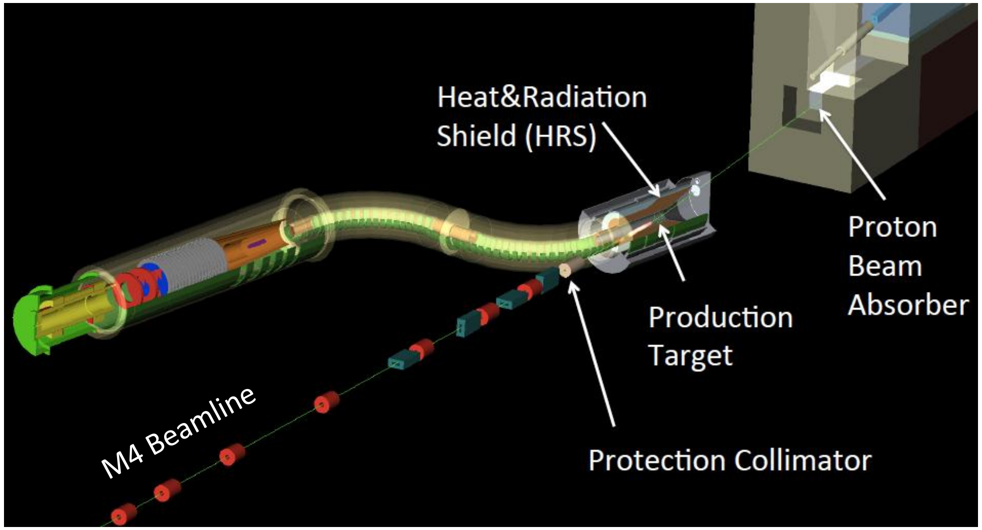
Eric Prebys



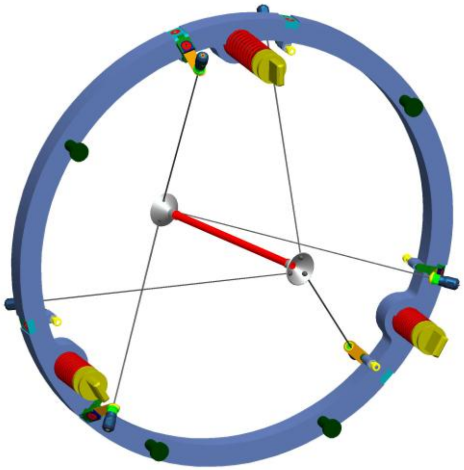




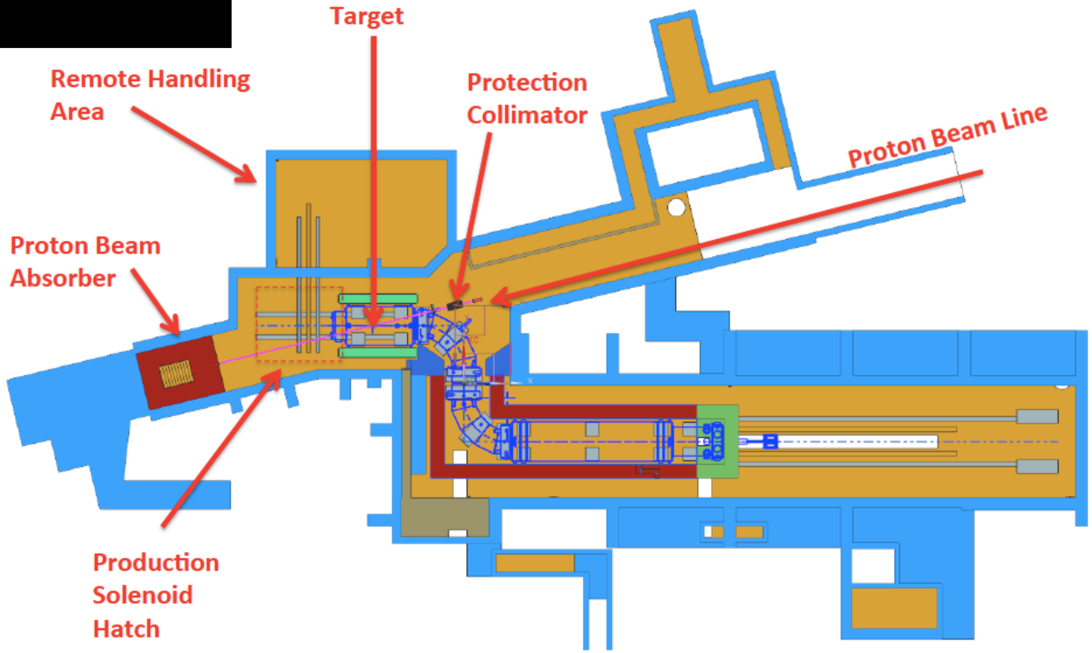
Mu2e production target station



- Produce π^- in target which decay in Transport Solenoid into μ^-
- Remote-handling area designed to deal with highly-radioactive components

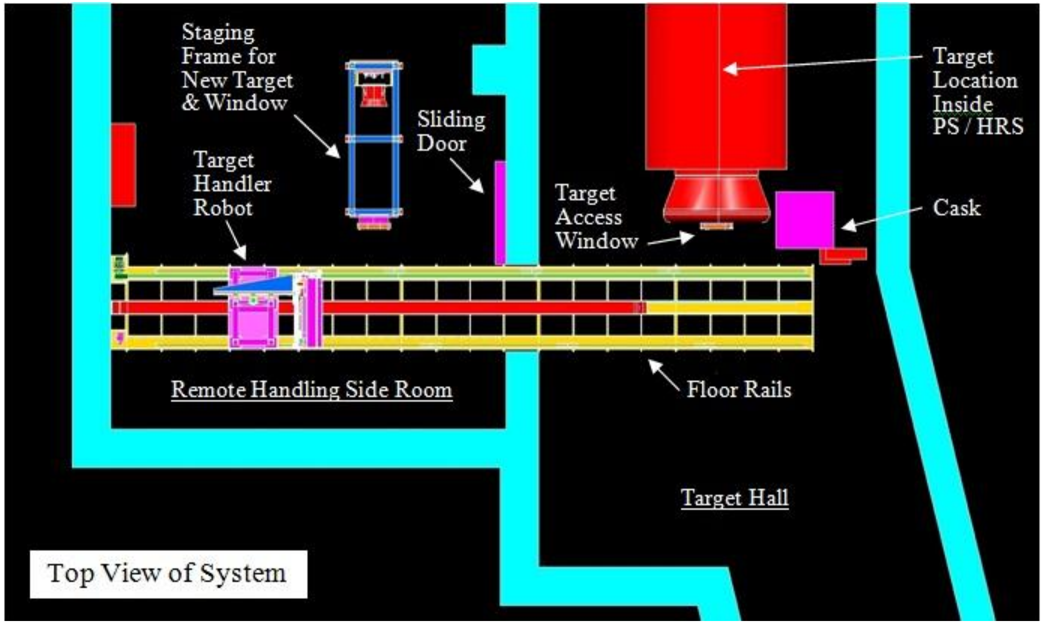


tungsten rod target



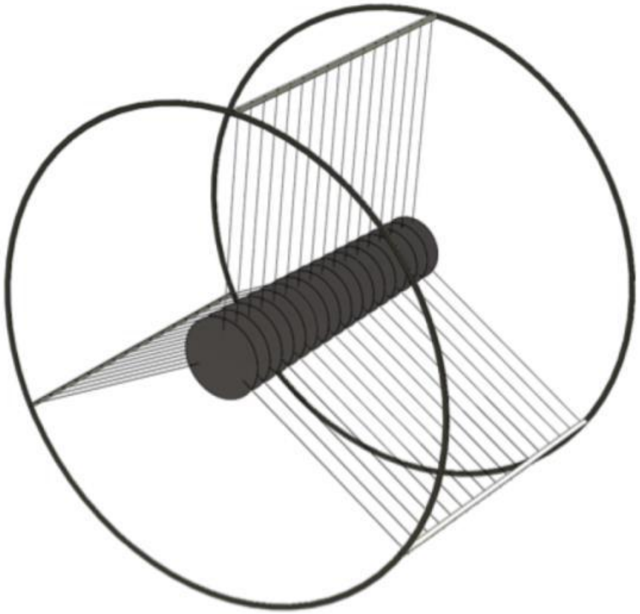
Mu2e target station remote handling

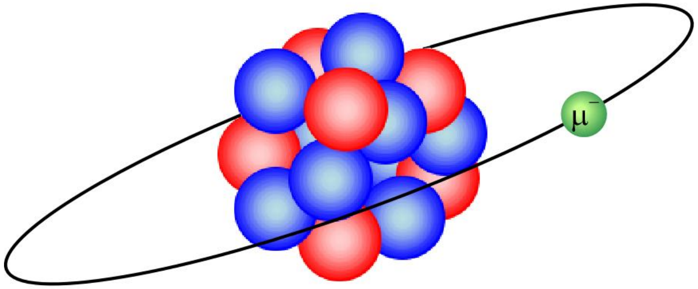
- Enter target hall from a separate side room
- Remove the target access window from the end of the PS
- Place target access window into waste storage cask
- Detach and remove old target assembly from mounted position
- Place old target assembly into waste storage cask
- Obtain new target assembly
- Place new target assembly into HRS bore and latch into mounted position
- Obtain new target access window (with new vacuum seal)
- Place new target access window to the end of the PS and tighten all bolts
- Exit target hall and return to side room
- The target remote handling system shall perform these tasks either autonomously or via operator remote control with no human entry into the target hall



Mu2e stopping target

- Aluminum foils, tapering in radius
- Supported by tungsten wires attached to the inner detector solenoid
- The muon is captured into an atomic orbital state of an aluminum nucleus
- The muon can decay in orbit (background)
- The muon may convert to an electron (signal)
  - Recoil off nucleus with kinematics of 2-body decay, m_e small compared to nucleus so E_e slightly less than m_μ

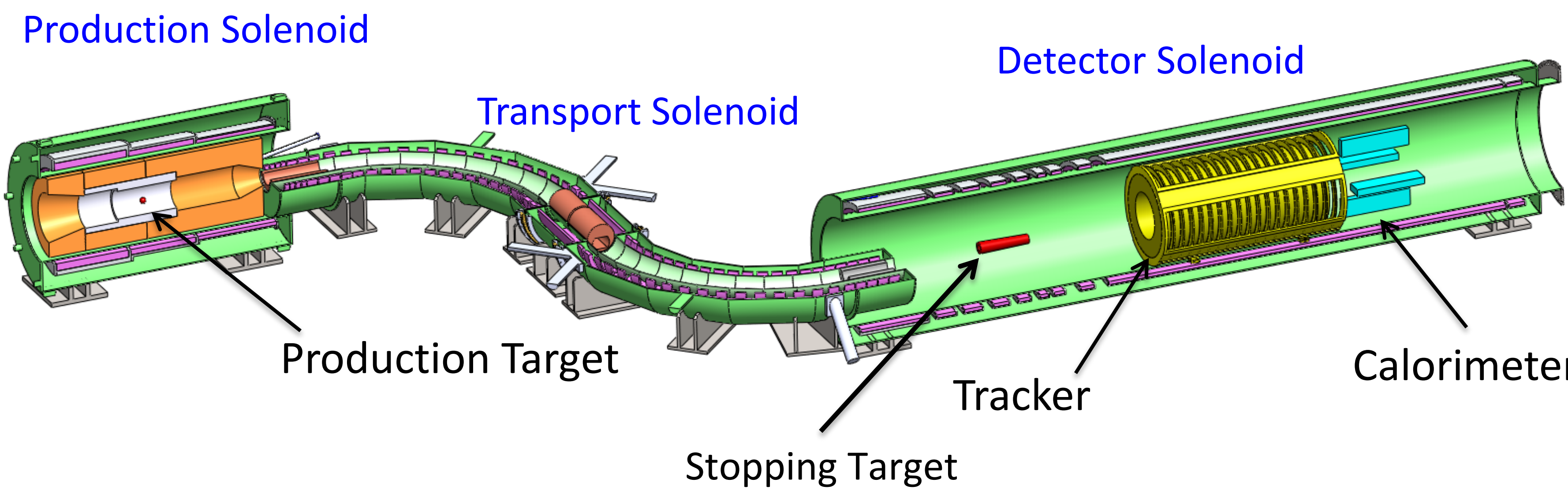




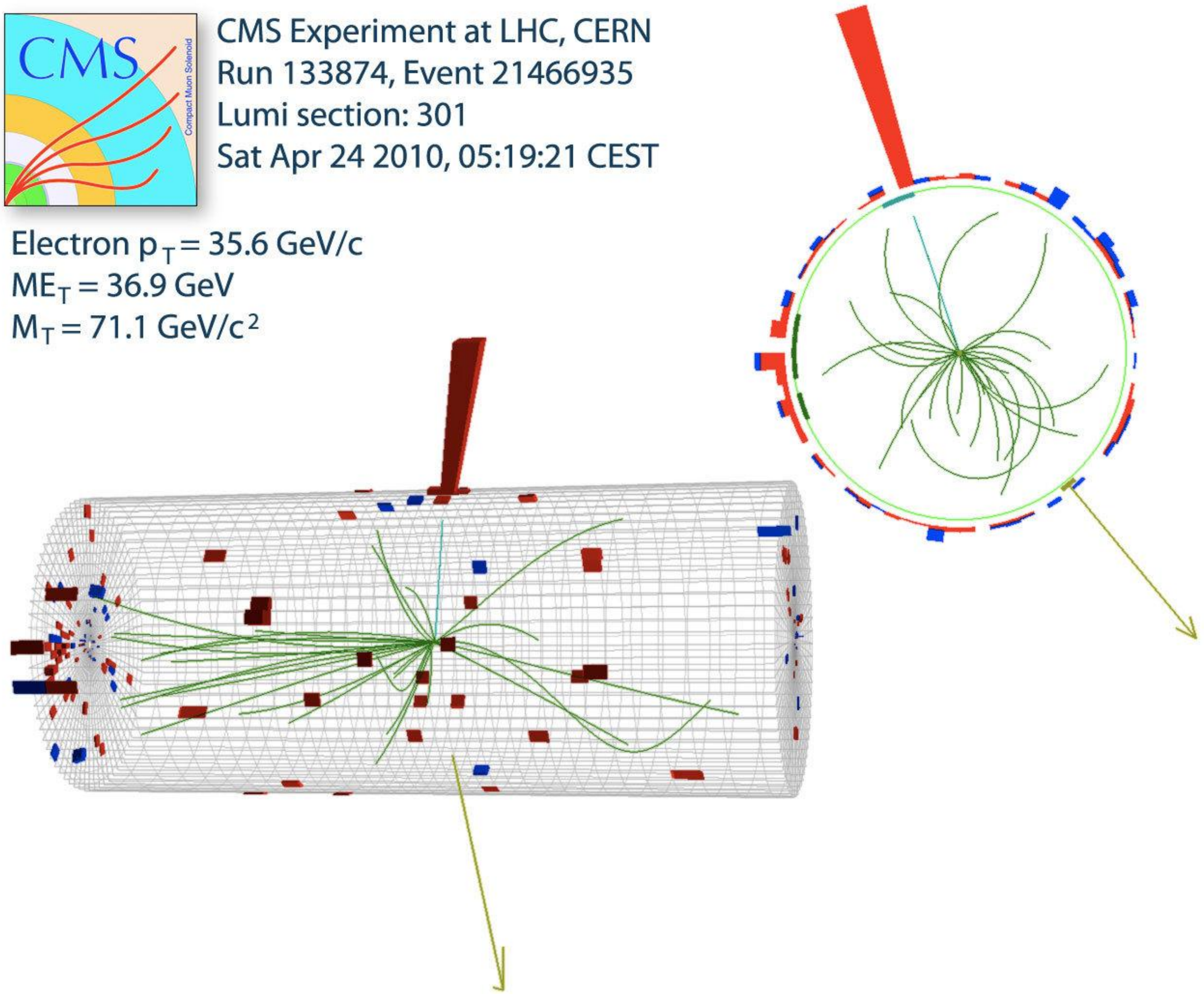
Fermilab

Mu2e superconducting solenoids

- Production solenoid
  - Capture secondaries off target and focus towards Transport Solenoid



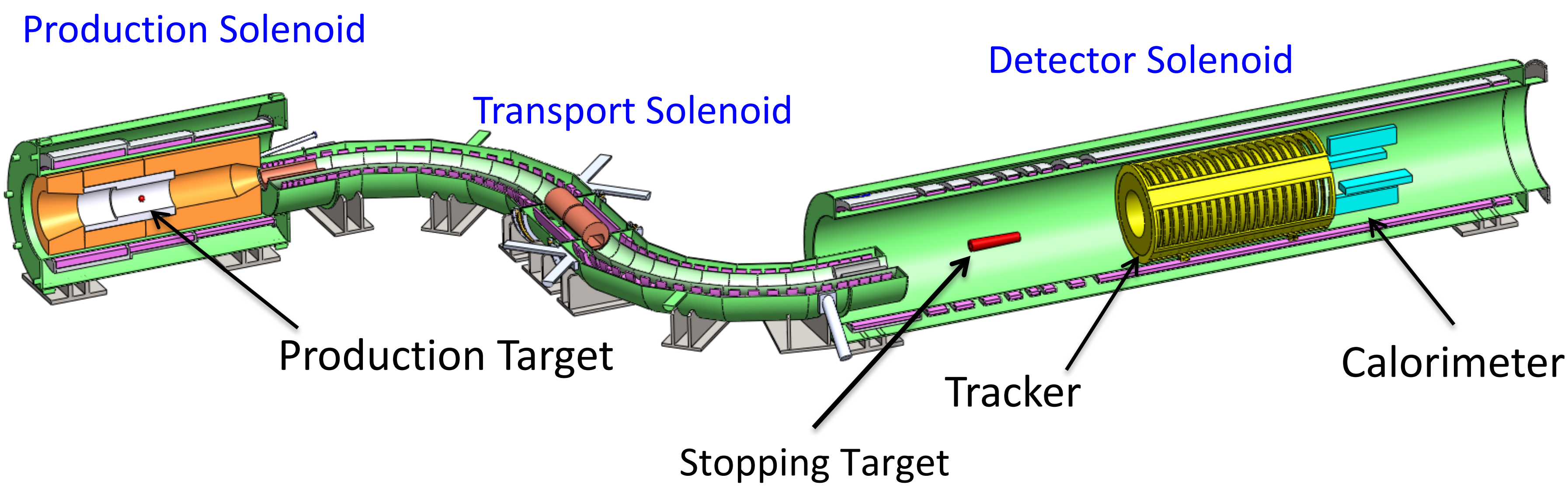
Aside on charged particles in solenoid magnetic field



Fermilab

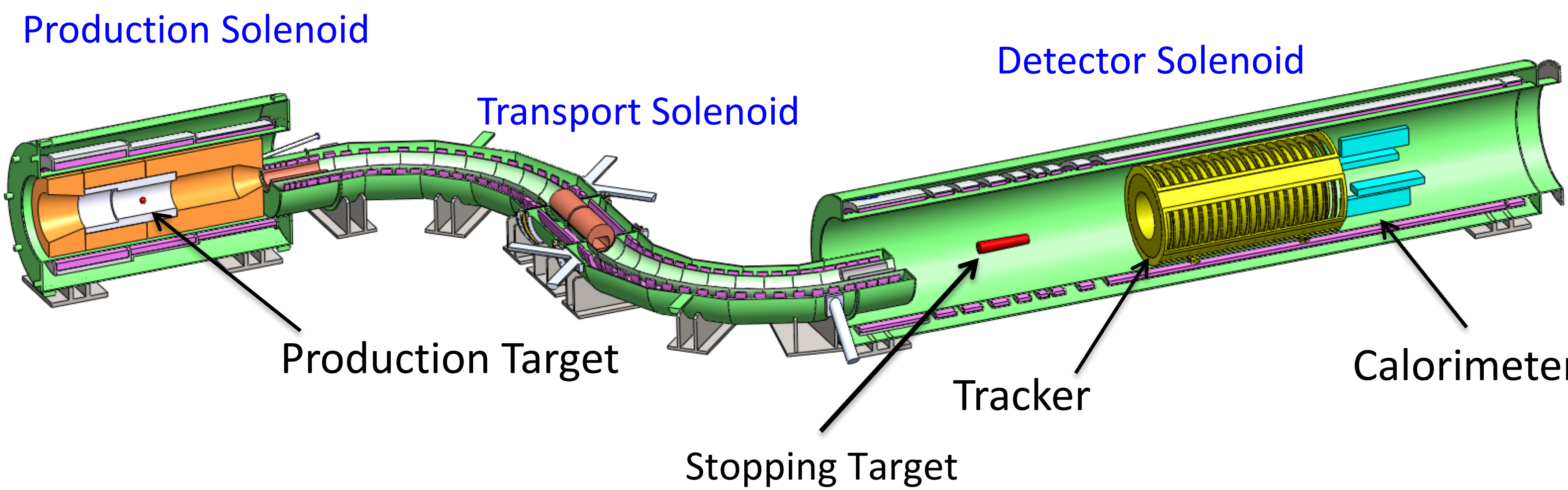
Mu2e superconducting solenoids

- Transport solenoid
  - Focus pions from target and muons from their decay to maximize capture
  - Remove positive particles, high-momentum negative particles, and neutral particles with help of two 90^{o} bends



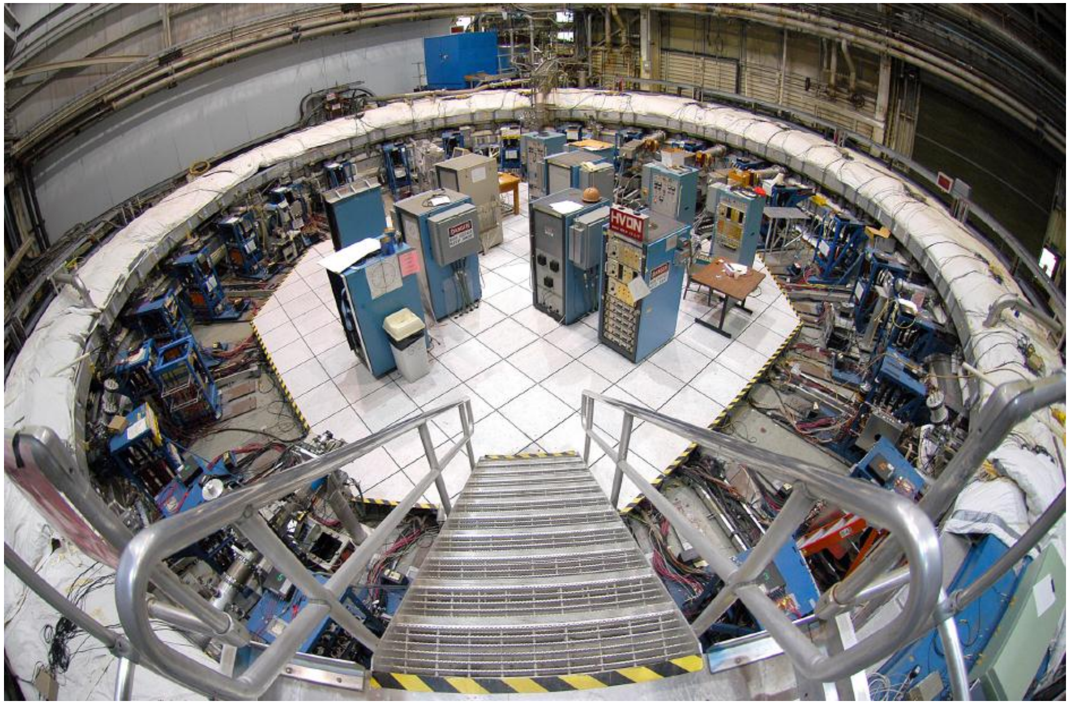
Mu2e superconducting solenoids

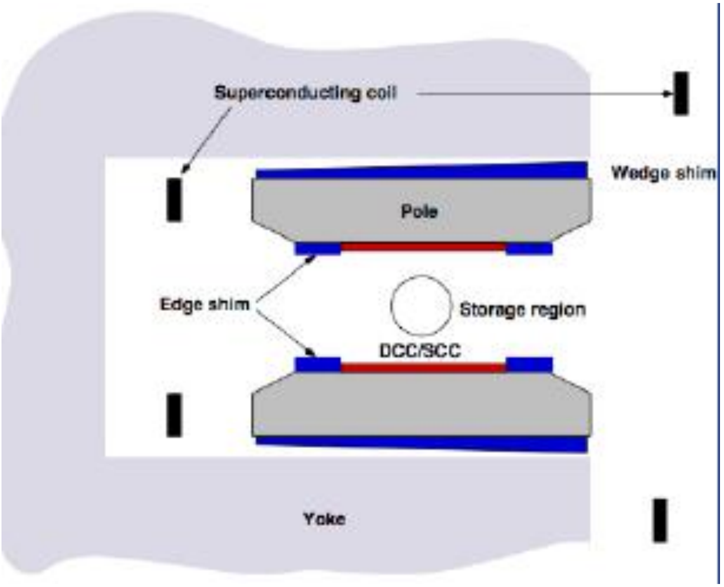
- Detector solenoid
  - Graded field in region of stopping target to focus conversion electrons toward the detector
  - Very uniform magnetic field in region of tracker to precisely measure energy of electrons



g-2 superconducting storage ring

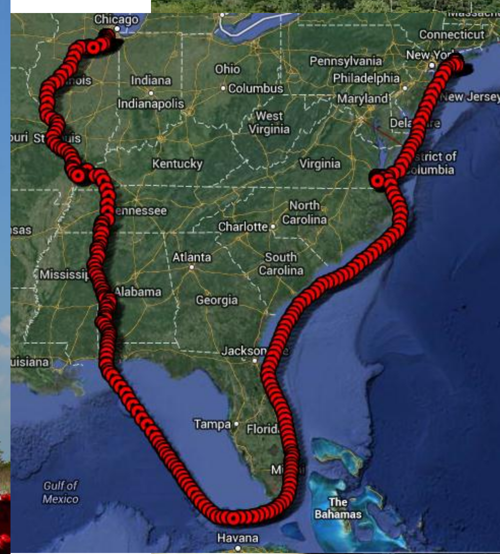
- Used in previous g-2 measurement at Brookhaven National Laboratory



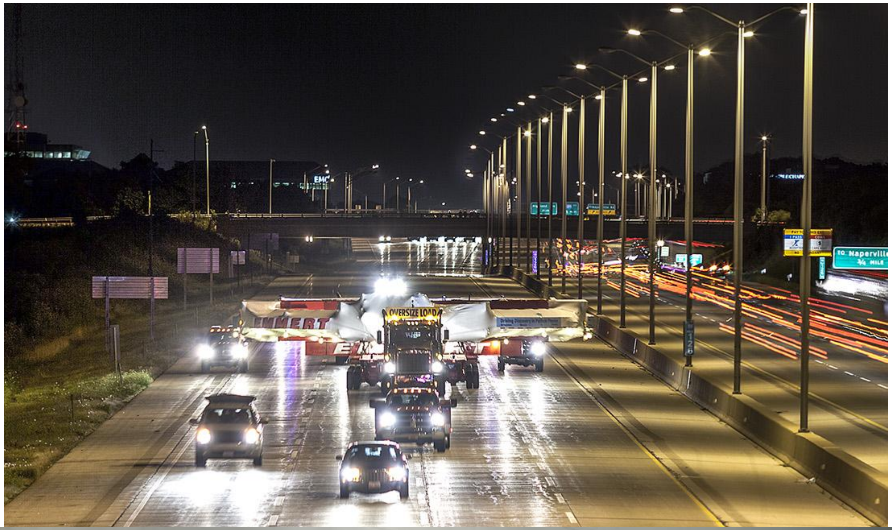


- Highly uniform magnetic field to allow precision measurement

Transport of g-2 storage ring from Brookhaven to Fermilab



g-2 storage ring



Timeline of beam to Muon Campus experiments

- g-2
  - Move ring into MC-1 building July
  - Ring cooled to superconducting temperatures spring 2015
  - Conversion of Antiproton Source to Muon Campus configuration has already begun and continues into 2017
  - Commissioning and begin data-taking in 2017
- Mu2e
  - Solenoid construction starting now and drives length of project
  - Beam commissioning beginning in 2017
  - Data-taking beginning in 2019